# Spectrum Sensing Techniques for Cognitive Radio Sensor Networks (CRSN)

by


**Hareesh K**

**Roll No. : 211EC4103**


A Thesis submitted for partial fulfillment for the degree of

**Master of Technology**

**in**

**Electronics and Communication Engineering**

**(Communication and Signal Processing)**


Dept. Electronics and Communication Engineering

**NATIONAL INSTITUTE OF TECHNOLOGY**

Rourkela, Orissa-769008, India


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## CERTIFICATE

This is to certify that the work in the thesis entitled, "***Spectrum Sensing Techniques for Cognitive Radio Sensor Networks (CRSN)***" submitted by ***Hareesh K*** is a record of an original research work carried out by him during 2012-2013 under my supervision and guidance in partial fulfillment of the requirement for the award of Master of Technology Degree in Electronics & Communication Engineering (Communication and Signal processing), National Institute of Technology, Rourkela. Neither this thesis nor any part of it has been submitted for any degree or diploma elsewhere.

Place: NIT Rourkela

Date: May 20, 2013

**Dr. Poonam Singh**

Professor

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Last but not least I would like to thank my parents and well-wishers.

**Hareesh K**

# Abstract

Cognitive radio sensor network (CRSN) is a recently emerging paradigm that aims to utilize the unique features provided by CR concept to incorporate additional capabilities to Wireless Sensor Network (WSN). A CRSN is a distributed network of wireless cognitive radio sensor nodes, which perform sensing operation on event signals and collaboratively communicate their readings over dynamically available spectrum bands in a multi-hop manner ultimately to satisfy the application-specific requirements. The realization of CRSN depends on addressing many difficult challenges, posed by the unique characteristics of both cognitive radio and sensor networks, and further amplified by their union.

Spectrum sensing technique plays an important role in the design of a CRSN. The first phase of this thesis work is concentrated in identifying the suitable spectrum sensing strategy for a CRSN by analyzing different spectrum sensing strategies and comparing together. The second phase involves a search for an optimum spectrum sensing scheme suitable for the resource constrained nature of CRSN by combining two or more sensing schemes together i.e. Hybrid Spectrum Sensing. The thesis concludes with a remark that hybrid spectrum sensing schemes are the most appropriate sensing schemes for CRSN under its unique constraints.

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# List of Acronyms & Abbreviations

| | |
|---|---|
| CRSN | Cognitive Radio Sensor Network |
| ED | Energy Detection |
| MF | Matched Filter |
| TDMA | Time Division Multiple Access |
| FDMA | Frequency Division Multiple Access |
| CDMA | Code Division Multiple Access |
| FH | Frequency Hopping |
| DS | Direct Sequence |
| WSN | Wireless Sensor Network |
| SS | Spectrum Sensing |
| SD | Spectrum Decision |
| DSA | Dynamic Spectrum Access |
| DSM | Dynamic Spectrum Management |
| CR | Cognitive Radio |
| QoS | Quality of Service |
| ISM | Industrial, Scientific, Medicine bands |
| ITU | International Telecommunication Union |
| IEEE | Institute of Electrical and Electronics Engineers |
| ETSI | European Telecommunications Standards Institute |
| CH | Cluster Head |
| OFDM | Orthogonal Frequency Division Multiplexing |

# Introduction

## 1.1 Introduction & Motivation

Enabling technology for ambient intelligence, wireless sensor networks (WSN) enables setting up an intelligent network capable of handling user requirements. But due to the independent design and deployment of WSN for many applications in the license exempt ISM band, the frequency band is extremely crowded [1]. Critical applications like health monitoring, forest monitoring etc. requires efficient and uninterrupted communication through sensor nodes in WSN. The event driven communication nature of WSN and the need to effectively reduce the spectrum crowding in WSN together suggests the idea of cognition to the wireless sensor network, the cognitive radio sensor network (CRSN) [2]. The task is to design CRSNs which performs well in fading and multipath channel environments within the constraints of sensor nodes.

Spectrum sensing in resource constrained, shadowing and fading environment of CRSN with receiver uncertainties is a more challenging task than conventional spectrum sensing in cognitive radio networks. Co-operative spectrum sensing techniques can improve the cognitive radio network performance by enhancing spectrum efficiency and spectrum reliability by effectively combating the destructive effects present in the CRSN environment at the cost of comprises in overhead traffic, power consumption, and complexity and control channels [3]. The identification of an appropriate spectrum sensing scheme for CRSN is a challenge within the constraints of wireless sensor nodes. Efforts have been concentrated to develop energy efficient and a cost effective co-operative spectrum sensing techniques which performs well in fading and shadowing environment.

## 1.2 Wireless Sensor Networks (WSN)

A wireless sensor network (WSN) consists of spatially distributed autonomous sensors to monitor physical or environmental outcomes, such as temperature, sound, pressure, etc. and to cooperatively communicate their data through the network to a main location. Recent developments in wireless communications and electronics have promoted the deployment of low cost, low-power and multifunctional sensor nodes that are small in size and communicate untethered in short distances [4]. These small sensor nodes, which consist of sensing, data processing, and communicating components, clarify the idea of sensor networks.

A sensor network is a union of a large number of sensor nodes that are densely placed either inside the phenomenon or very close to it. The location of sensor nodes need not be engineered or predetermined. This permits random deployment in inaccessible terrains or disaster relief operations. But, this also implies sensor network protocols and algorithms must possess self-organizing capabilities. Another unique property of sensor networks is the co-operative effort among sensor nodes. Sensor nodes are equipped with an onboard processor. Rather sending the raw data to the nodes responsible for the decision fusion, their processing abilities to locally carry out simple computations and transmit only the required and partially processed data are highlighted.

The WSN is composed of "nodes" – from a few to several hundreds or even thousands, where each node is linked to one or several sensors. Each such sensor network node consists of several parts: a radio transceiver with an inbuilt antenna or connection to an outer antenna, a microcontroller, an electronic circuit for connecting with the sensors and an energy source, usually a power supply in battery form or an embedded form of energy harvesting. A sensor node might vary in size from that of a matchbox down to the size of a grain of dust, although functioning "motes" of genuine microscopic dimensions have yet to be formed. The sensor node cost is variable similarly, from a few to hundreds of dollars, depending on the complexity of the individual sensor nodes. Size and cost limitations on sensor nodes result in corresponding constraints on resources such as memory, energy, computational speed and communications bandwidth [5]. The topology of the WSNs can range from a simple star network to an advanced multi-hop wireless mesh network. The transmission technique between the hops of the network can be routing or flooding.

### 1.2.1 Characteristics of WSN

The main Features of a WSN include:

- Power Supply for nodes using batteries or energy harvesting
- Ability to withstand node failures
- Mobility of sensor nodes
- Communication problems
- Heterogeneity of sensor nodes
- large scale deployment
- capability to cope with difficult environmental conditions
- Ease of use

Sensor nodes can be viewed as small computers, extremely simple in terms of their interfaces and components. They normally consist of a processing unit with limited computational power and memory, sensors or MEMS (including specific conditioning mechanism), a communication device (usually radio transceivers or alternatively optical), and a power source usually a battery. Other possible inclusions are energy harvesting parts, secondary ASICs, and secondary communication devices (e.g. RS-232 or USB).

### 1.2.2 Potential Applications of WSN

1. Military applications

- Monitoring inimical forces
- Observing  friendly forces and equipment
- Targeting
- Battle damage assessment
- Nuclear, biological, and chemical attack detection

2. Environmental Applications

- Microclimates
- Forest Fire Detection
- Flood Detection
- Precision Agriculture

3. Health applications

- Remote monitoring of physiological report
- Tracking and observing patients and doctors in a hospital
- Drug administration
- Elderly assistance

4. Home applications

- Home automation
- Instrumented environment
- Automated meter reading

5. Commercial applications

- Climate control in industrial and office buildings
- Inventory control
- Vehicle tracking and detection
- Traffic flow surveillance

## 1.3 Spectrum Crowding in WSN

Wireless sensor network (WSN) is an exciting new technology with application to environmental monitoring, medical care, smart buildings, agriculture, factory monitoring and automation, and various military applications. A WSN can also be treated as an underlying infrastructure that will be an integral part of future ubiquitous and embedded computing applications. With the exciting advancement in wireless sensor network (WSN) research, it is envisioned that in 5-12 years, the world will be full of low power wireless sensor devices. Due to the independent design and advancement, in addition with the unexpected dynamics during deployment of co-existing networks and devices, the limited frequency band will be extremely crowded [6]. Even, existing electric appliances like microwaves make the congestion even worse.

The development of mobile and ubiquitous devices increased the demand for communication and consequently the competition for frequency spectrum. Most of these devices use the ISM (Industrial, Scientific and Medical) frequency band, which does not require a license for operation. However, this band is used in applications such as cordless phones, remote control, microwave ovens and audio and video systems. The diversity of applications, along with the numerous communication standards employing the ISM frequency, has increased the level of interference and even caused the unavailability of spectrum in certain regions [7]. In some locations the 2.4 GHz frequency band reaches an occupancy of up to 90%.

Table 1.1

Operating Spectrum Bands of Commercial WSN Transceivers and Overlapping Wireless Systems

| Sensor node platforms | Radio chip | Operating bands | Overlapping wireless systems |
|---|---|---|---|
| *Bean [5], BTnode [6], Mica2 [7], MANTIS Nymph [8]* | Chipcon (TI Norway) CC1000 | 315, 433, 868, 915 MHz | Fixed, Mobile, Amateur, Satellite, Radiolocation, Broadcasting, Telemetry, ZigBee |
| *IMote [9], MicaZ [10], SenseNode [11], XYZ [12], Sentilla Mini [13], TelosB [14]* | Chipcon (TI Norway) CC2420 | 2.4 GHz | Fixed, Mobile, Amateur Radio as secondary, 802.11b/g/n, Telemetry, Bluetooth, ZigBee |
| *Mica [7], weC* | RF Monolithics TR1000 | 916.3 - 916.7 MHz | Fixed, Mobile, Broadcasting, Telemetry, ZigBee |
| *ANT [15]* | Nordic nRF24AP1 | 2.4 GHz | Fixed, Mobile, Amateur Radio as secondary, Telemetry, 802.11b/g/n, Bluetooth, ZigBee |
| *EyesIFX v1 and v2 [16]* | Infineon TDA5250 | 868 - 870 MHz | Fixed, Mobile, Broadcasting, Telemetry, ZigBee |
| *Iris [17]* | Atmel AT86RF230 | 2.4 GHz | Fixed, Mobile, Amateur Radio as secondary, Telemetry, 802.11b/g/n, Bluetooth, ZigBee |

## 1.4 **Cognitive Radio (CR)**

Cognitive radio is the key enabling technology that enables next generation communication networks, also known as dynamic spectrum access (DSA) networks, to utilize the spectrum more efficiently in an opportunistic fashion without interfering with the primary users. It is defined as a radio that can change its transmitter parameters according to the interactions with the environment in which it operates [8]. It differs from conventional radio devices in that a cognitive radio can equip users with cognitive capability and reconfigurability. Cognitive capability defines the ability to sense and gather information from the surrounding environment, such as information about transmission frequency, bandwidth, power, modulation, etc. With this capability, secondary users can identify the best available spectrum. Reconfigurability is the ability to rapidly adapt the operational parameters according to the sensed information in order to achieve the optimal performance. By utilizing the spectrum in an opportunistic fashion, cognitive radio allows secondary users to sense the portion of the spectrum are available, select the best available channel, co-ordinate spectrum access with other users, and leave the channel when a primary user reclaims the spectrum usage right.

### 1.4.1 Cognitive Radio Characteristics

The dramatic increase of service quality and channel capacity in wireless networks is severely limited by the scarcity of energy and bandwidth, which are the two basic resources for communications. Therefore, researchers are currently focusing their attention on new communications and networking paradigms that can intelligently and efficiently utilize these scarce resources [9]. Cognitive radio (CR) is one critical enabling technology for future communications and networking that can utilize the limited network resources in a more efficient and flexible way. It differs from customary communication paradigms in a way the radios/devices can adapt their operating parameters, such as transmission power, frequency, modulation type, etc., to the variations of the surrounding radio environment. Before CRs adjust their operating mode to environment variations, they must first gain necessary information from the radio environment. This type of characteristics is referred to as cognitive capability, which enables CR devices to be aware of the transmitted waveform, radio frequency (RF) spectrum, communication network type/protocol, geographical information, locally available resources and services, user needs, security policy, and so on. After CR devices gather their needed information from the radio environment, they can dynamically change their transmission parameters according to the sensed environment variations and achieve optimal performance, which is referred to as reconfigurability [10].

### 1.4.2 Cognitive Radio Functions

A typical duty cycle of CR, as illustrated in Fig.1.1, includes detecting spectrum white space, selecting the best frequency range, coordinating spectrum access with other users and vacating the frequency when a primary user appears. Such a cognitive cycle is supported by the following functions:

- **Spectrum sensing and analysis;**
- **Spectrum management and handoff;**
- **Spectrum allocation and sharing.**

Through spectrum sensing and analysis, CR can detect the spectrum white space (see Fig.1.2), i.e., a portion of frequency band that is not being used by the primary users, and utilize the spectrum [11]. On the other hand, when primary users start using the licensed spectrum again, CR can detect their activity through active sensing, so that no harmful interference due to secondary users' transmission.

After recognizing the spectrum white space by sensing, spectrum management and handoff function of CR enables secondary users to choose the best frequency band and hop among multiple bands according to the time varying channel characteristics to meet various Quality of Service (QoS) requirements. when a primary user reclaims his/her frequency band, the secondary user that is using the licensed band can direct his/her transmission to other available frequencies, according to the channel capacity determined by the noise and interference levels, path loss, channel error rate, holding time, and etc. In dynamic spectrum access, a secondary user may be sharing the spectrum resources with primary users, other secondary users, or both. A good spectrum allocation and sharing mechanism is critical to achieve high spectrum efficiency [12]. Since primary users own the spectrum rights, when secondary users exist in a licensed band with primary users, the secondary user's interference level should be limited by a certain threshold.

When many secondary users share a frequency band, their access should be co-ordinated to avoid collisions and interference.

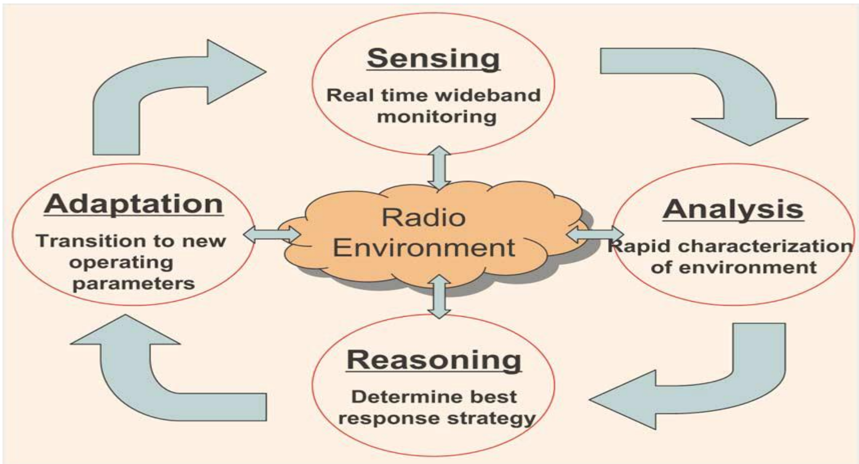


Fig. 1.1 Cognitive cycle.

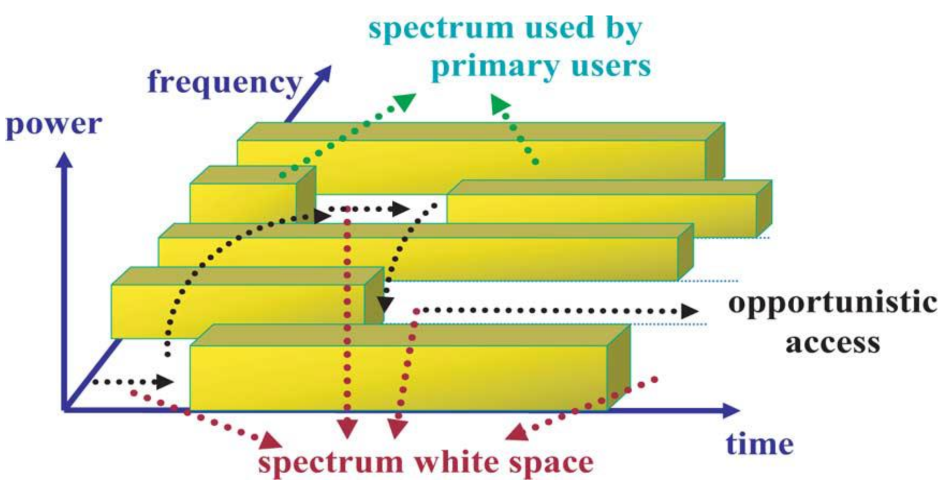


Fig.1.2 Illustration of spectrum white space

## 1.5 Salient Features of Dynamic Spectrum Access (DSA)

- Opportunistic channel usage for bursty traffic: Upon the detection of an event in WSN, sensor nodes generate traffic of packet bursts. At the same time, in densely deployed sensor networks, a large number of nodes within the event area try to acquire the channel. This increases probability of collisions, and hence, decreases the overall communication reliability due to packet losses leading to excessive power consumption and packet delay [13]. Here, sensor nodes with cognitive radio capability may opportunistically access to multiple alternative channels to alleviate these potential challenges.

- Dynamic spectrum access: In general, the existing WSN deployments assume fixed spectrum allocation. However, WSN must either be operated in unlicensed bands, or a spectrum lease for a licensed band must be obtained. Generally, high costs are associated with a spectrum lease, which would, in turn, amplify the overall cost of deployment. This is also contradictory with the main design principles of WSN. On the other hand, unlicensed bands are also used by other devices such as IEEE802.11 wireless local area network (WLAN) hotspots, PDAs and Bluetooth devices as shown in Table I. Therefore, sensor networks experience crowded spectrum problem [14]. Hence, in order to maximize the network performance and be able to co-operate efficiently with other types of users, opportunistic spectrum access schemes must be utilized in WSN as well.

- Using adaptability to reduce power consumption: Time varying nature of wireless channel causes energy consumption due to packet losses and retransmissions. Cognitive radio capable sensor nodes may be able to change their operating parameters to adapt to channel conditions. This capability can be used to increase transmission efficiency, and help reduce power used for transmission and reception.

- Overlaid deployment of multiple concurrent WSN: With the increased usage of sensor networks, one specific area may host several sensor networks deployed to operate towards fulfilling specific requirements of different applications [15]. In this case, dynamic spectrum management may significantly contribute to the efficient co-existence of spatially overlapping sensor networks in terms of communication performance and resource utilization.

- Access to multiple channels to conform to different spectrum regulations: Each country has its own spectrum regulation rules. A certain band available in one country may not be available in another. Traditional WSN with a preset working frequency may not be deployed in cases where manufactured nodes are to be deployed in different regions [16].

However, if nodes were to be equipped with cognitive radio capability, they would overcome the spectrum availability problem by changing their communication frequency.

## 1.6 Cognition in WSN

The increasing demand for wireless communication introduces efficient spectrum utilization. To meet this challenge, cognitive radio has emerged as the key technology, with opportunistic access to the spectrum. The potential advantages introduced by cognitive radio are improving spectrum utilization and increasing communication quality. These features match the unique requirements and challenges of resource-constrained multi-hop wireless sensor networks (WSN) [17]. Furthermore, dynamic spectrum access stands as very promising and spectrum-efficient communication paradigm for WSN due to its event-driven communication nature, with bursty traffic depending on the event characteristics. Opportunistic spectrum access may also help eliminate collision and excessive contention delay incurred by dense deployment of sensor nodes. Clearly, it is conceivable to adopt cognitive radio capability in sensor networks, which, in turn yields a new sensor networking paradigm, i.e., cognitive radio sensor networks (CRSN).

## 1.7 Cognitive Radio Sensor Networks (CRSN)

It is conceivable to provide wireless sensor networks with the capabilities of cognitive radio and dynamic spectrum management. This defines a new sensor network paradigm, i.e., Cognitive Radio Sensor Networks (CRSN) [18]. In general, a CRSN can be defined as a distributed network of wireless cognitive radio sensor nodes, which sense an event signal and communicate their readings dynamically over available spectrum bands in a multi-hop manner ultimately to satisfy the application-specific requirements.

The realization of CRSN depends on addressing many difficult challenges, posed by the unique characteristics of both cognitive radio and sensor networks, and further amplified by their union. The inherent resource constraints of sensor nodes, additional communication and processing demand imposed by cognitive radio capability, design of low-cost and power-efficient cognitive radio sensor nodes, efficient opportunistic spectrum access in densely deployed sensor networks, multi-hop and collaborative communication over licensed and unlicensed spectrum bands are primary obstacles to the design and practical deployment of CRSN [19].

## 1.8 Thesis Contributions

The work reported herein investigates the spectrum sensing aspects of CRSN. Energy detection inherently the simplest spectrum sensing strategy for Cognitive Radio (CR) fails to deliver at low SNR conditions. An adaptive threshold based energy detector is considered to improve the throughput and to reduce the interference as well. Hybrid spectrum sensing the appropriate spectrum strategy for CRSN is discussed and then proposed a new hybrid spectrum sensing scheme comprised of energy detector and eigen value based detector.

## 1.9 Thesis Outline

The first two chapters of the thesis give an introduction to Wireless Sensor Networks (WSN) and its applications, Cognitive Radio, the features of Dynamic Spectrum Access, Cognitive Radio Sensor Networks (CRSN) and background literature survey. The third chapter presents a detailed discussion about CRSN, Dynamic Spectrum Management Aspects in CRSN, Communications in CRSN and potential application areas of CRSN. The main theme of this thesis is focused on various spectrum sensing techniques applied for Cognitive Radio Sensor Networks is discussed in chapter 4. Transmitter based detection techniques like Energy Detection, Matched Filter, Cyclo-Stationary Detector and Eigen Value based Detectors are covered in depth. Co-operative Spectrum Sensing and its favorability to CRSN is discussed then followed with the discussion of adaptive threshold based energy detectors to improve the throughput and to reduce the interference. Simulation results are presented to analyze the performance of various spectrum sensing schemes. Chapter 5 focus on Hybrid Spectrum Sensing Schemes which are a combination of two or more Detection Schemes and analyze its performance in a CRSN environment.

# Cognitive Radio Sensor Networks (CRSN): A Review

## 2.1 CRSN Architecture

Cognitive radio sensor nodes forms a wireless communication architecture of CRSN as shown in Fig.2.1 over which the information obtained from the field is conveyed to the sink in multiple hops. The main duty of the sensor nodes is to perform sensing on the environment. In addition to this conventional sensing duty, CRSN nodes also perform sensing on the spectrum. Depending on the spectrum availability, sensor nodes transmit their readings in an opportunistic manner to their next hop cognitive radio sensor nodes, and ultimately, to the sink [20]. The sink may be also equipped with cognitive radio capability, i.e., cognitive radio sink. In addition to the event readings, sensors may exchange additional information with the sink including control data for group formation, spectrum allocation, spectrum handoff-aware route determination depending on the specific topology.

A typical sensor field contains resource-constrained CRSN nodes and CRSN sink. However, in certain application scenarios, special nodes with high power sources, i.e., actors, which act upon the sensed event, may be part of the architecture as well. These nodes perform additional tasks like local spectrum bargaining, or acting as a spectrum broker. Therefore, they may be actively part of the network topology. It is assumed that the sink has unlimited power and a number of cognitive transceivers, enabling it to transmit and receive multiple data flows concurrently.

### 2.1.1 CRSN Node Structure

CRSN node hardware structure is mainly composed of sensing unit, processor unit, memory unit, power unit, and cognitive radio transceiver unit as abstracted in Fig.2.2 In specific applications, CRSN nodes may have mobilization and localization units as well. The main difference between the hardware structure of classical sensor node and CRSN nodes is the cognitive radio transceiver of CRSN nodes [21]. Cognitive radio unit enables the sensor nodes to dynamically adapt their communication parameters such as carrier frequency, transmission power, and modulation.

CRSN nodes also inherit the limitations of conventional sensor nodes in terms of power, communication, processing and memory resources. These limitations impose restrictions on the features of cognitive radio as well. For example, CRSN nodes may perform spectrum sensing over a limited band of the spectrum due to processing, power, and antenna size constraints [22]. Consequently, CRSN nodes are generally constrained in terms of the degree of freedom provided by the cognitive radio capability as well.

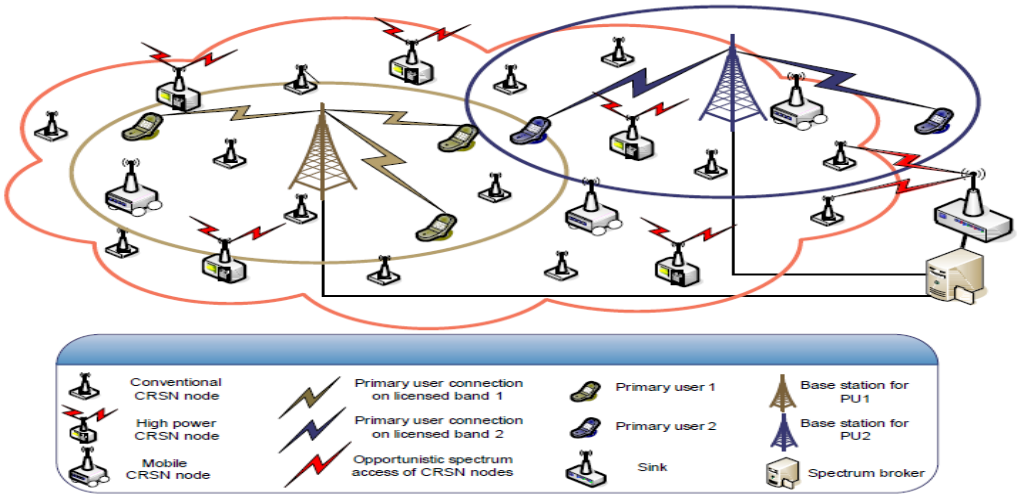


Fig. 2.1 A typical cognitive radio sensor network (CRSN) architecture.

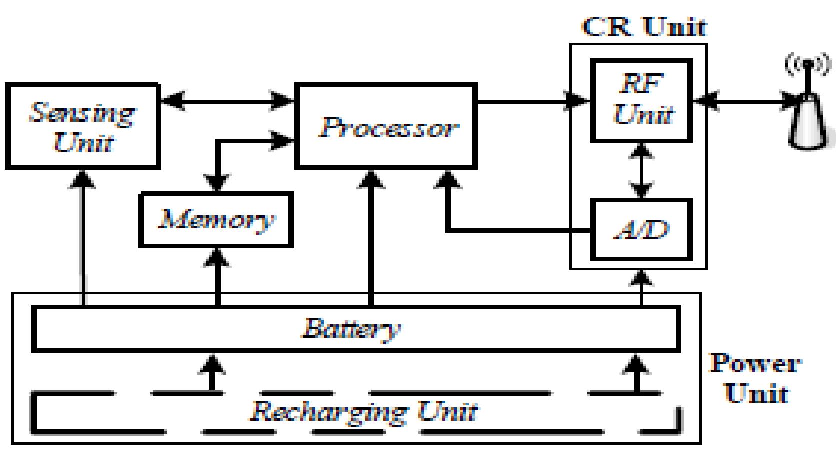


Fig. 2.2 Hardware structure of a cognitive radio sensor node.

### 2.1.2 CRSN Topology

According to the application requirements, cognitive radio sensor networks may exhibit different network topologies as explored in the following [23].

1) Ad Hoc CRSN: Without any infrastructural element, inherent network deployment of sensor networks yields an ad hoc cognitive radio sensor network as shown in Fig. 3. Nodes send their readings to the sink in multiple hops, in an ad-hoc way.

In ad hoc CRSN, spectrum sensing may be performed by each node individually or collaboratively in a distributed way. Similarly, spectrum allocation can also be based on the individual decision of sensor nodes. This topology imposes almost no communication overhead in terms of control data. However, due to hidden terminal problem, spectrum sensing results may be inaccurate, causing performance degradation in the primary user network.

2) Clustered CRSN: In general, it is essential to designate a common channel to exchange various control data, such as spectrum sensing results, spectrum allocation data, neighbor discovery and maintenance information. Most of the time, it may not be possible to find such common channel available throughout the entire network. However, it has been shown in that finding a common channel in a certain restricted locality is highly possible due to the spatial correlation of channel availability. Therefore, a cluster-based network architecture as in Fig.2.3 a.is an appropriate choice for effective operation of dynamic spectrum management in CRSN.

In this case, cluster-heads may also be assigned to handle additional tasks such as the collection and dissemination of spectrum availability information, and the local bargaining of spectrum. To this end, new cluster-head selection and cluster formation algorithms may be developed for CRSN which jointly consider the inherent resource constraints as well as the challenges and requirements of opportunistic access in CRSN.

3) Heterogeneous and Hierarchical CRSN: In some cases, CRSN architecture may incorporate special nodes equipped with more or renewable power sources such as the actor nodes in wireless sensor and actor networks (WSAN). These nodes may have longer transmission ranges, and hence, be used as relay nodes much like the mesh network case. This forms a heterogeneous

and multi-layer hierarchical topology consisting of ordinary CRSN nodes, high power relay nodes, e.g., cognitive radio actor nodes, and the sink as shown in Fig.2.3 b.

While the presence of capable actor nodes may be exploited for effective opportunistic access over the CRSN, the associated heterogeneity brings additional challenges. Among the others, sensor and actor deployment, increased communication overhead due to hierarchical coordination, and the need for cognitive radio capability over the actor nodes need to be addressed.

4) Mobile CRSN: When some or all of the architectural elements of a CRSN are mobile, this yields a more dynamic topology, i.e., a mobile CRSN. For example, the sensor nodes, actors if exist, and even the sink might be mobile depending on the specific application and deployment scenario.

Clearly, mobility amplifies the existing challenges on most of the aspects of CRSN. First of all, the dynamic nature of the topology requires mobility-aware dynamic spectrum management solutions over resource-constrained CRSN nodes. Moreover, cognitive radio communication protocols for CRSN must consider mobility as well. Therefore, this specific CRSN architecture needs a thorough investigation of the challenges and solution techniques.

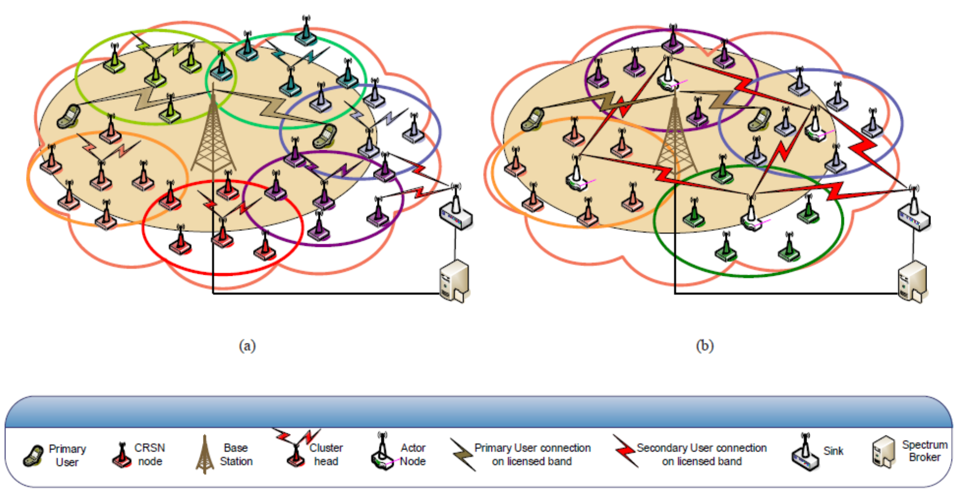


Fig. 2.3 Possible network topologies for CRSN (a) Clustered (b) heterogeneous hierarchical.

## 2.2 Dynamic Spectrum Management in CRSN

The realization of cognitive radio sensor networks primarily require an efficient spectrum management framework to regulate the dynamic spectrum access of densely deployed resource-constrained sensor nodes [24]. The major challenges and open research issues regarding such dynamic spectrum management framework for CRSN are explored in this section.

### 2.2.1 Spectrum Sensing

Spectrum sensing is one of the major functionalities distinguishing CRSN from traditional WSN. Since nodes can operate on spectrum bands of the licensed primary users in an opportunistic manner, they must gather spectrum usage information via spectrum sensing prior to transmission [25]. In the literature, there exist various spectrum sensing methods, which are examined below in terms of how they can apply to CRSN.

• **Energy detection**: Inherent constraints of CRSN nodes mandate for a simpler spectrum sensing technique such as energy detection method. This method is popular even in cognitive radio networks, where nodes are typically less power constrained and have more computational power. The idea is to measure the received energy on the specific portion of the spectrum, i.e., channel, for a certain period of time. If the measured energy is below a threshold value, the channel is considered available. Its simplicity and low signal processing requirement make this method very attractive for CRSN [26]. However, it has a number of drawbacks. Energy detection requires longer measurement duration to achieve a certain performance level compared to matched filter method. Furthermore, the performance of this method highly depends on variations of the noise power level. Therefore, in case of a small increase in detected energy, it is impossible to understand whether the reason is a primary user activity or an increase noise power level.

• **Matched filter**: It has been shown that the optimal spectrum sensing method for the cognitive radio with the presence of Gaussian noise is the matched filter method. However, this approach requires a priori knowledge about the transmission of the primary user. Since it is a coherent detection method, it requires synchronization with the primary user [27]. In cases, where PU transmission characteristics are available, matched filter-based detection may be employed. However, most of the time, such assumption is unrealistic. Furthermore, CRSN nodes need additional dedicated circuitry for each encountered primary user type. This considerably increases the cost and complexity for low-end sensor nodes.

• **Feature detection**: This method can be used when certain features of the primary user transmission such as carrier frequency and cyclic prefixes are known. Feature detection method takes advantage of the cyclo-stationary features of the PU signal. Unlike noise, the PU signal has spectrum correlation due to its inherent cyclo-stationarity. By making use of this correlation, the PU signal inside the noise can be detected. Thus, feature detection method is very robust against variations of noise [28]. However, this additional capability comes with the cost of increased complexity, which typical CRSN nodes may not be able to provide. Hence, feature detection is more suitable to special CRSN cases where the network includes nodes with greater computational power.

• **Eigen Value Based Detection**: Eigen value based spectrum sensing relies on algorithms developed on the Eigen values of the sample co-variance matrix, determined from the received signal at the cognitive sensing node [29]. Eigen value based spectrum sensing can be mainly employed using two algorithms, based on the ratio of maximum to minimum Eigen value (MME) and based on the ratio of average signal power to the minimum Eigen value (EME).

Most of the Spectrum sensing methods devised for cognitive radio not suitable for CRSN as they are designed without considering the unique challenges posed by the resource constraints of sensor nodes as follows:

- **Hardware limitations** - It is not feasible to equip CRSN nodes with highly capable processors and A/D units. Thus, complex detection algorithms cannot be used. Spectrum sensing must be performed with limited node hardware.
- **Minimum sensing duration** - Keeping the transceiver on even just for spectrum listening causes excessive power consumption. While sensing accuracy increases with duration, spectrum sensing must be achieved in short sensing duration.
- **Reliable sensing** - Secondary users can operate on licensed bands, unless they do not interfere with primary users. For avoiding interference on primary user, spectrum sensing must be reliable.

The first two of these challenges are unique to CRSN. The last one is a concern for cognitive radio networks too; however, due to limitations of the cognitive radio sensor node, techniques developed for cognitive radio networks cannot be directly applied to CRSN. Therefore, additional research must be conducted on spectrum sensing for CRSN along the following open research issues:

• **Hybrid sensing techniques**: A possible way to obtain spectrum information with minimum sensing duration and low computational complexity is to use hybrid sensing techniques, which is a balanced combination of the sensing approaches above. For example, energy detection may be used on a broader band to have an idea about which portions of the spectrum may be available [30]. Based on this information, more accurate sensing methods can be performed over selected potential channels. Therefore, hybrid sensing techniques addressing the tradeoff between sensing accuracy and complexity must be investigated.

• **Cooperative sensing**: When nodes rely only on their own spectrum sensing results, they may not be able to detect the primary user due to shadowing. Spectrum sensing duty may be distributed among the nodes to increase sensing accuracy [31]. Achieving sensing in a distributed manner is called cooperative sensing. While cooperative sensing yields better sensing results, it also imposes additional complexity and communication overhead. New cooperative sensing method, requiring minimum amount of extra packet transmission and having minimum impact on the sleep cycles of the node, is an open research issue.

• **Sensing based on collaborative PU statistics**: If it is possible to obtain channel usage statistics of the primary users, it may be possible to develop more efficient sensing methods. Even if PU statistics are not available, nodes may collectively obtain these statistics by continuously sharing their distributed spectrum sensing results. Intelligent and collaborative methods, which estimate and then make use of primary user channel usage statistics, must be studied.

### 2.2.2 Spectrum Decision

CRSN nodes must analyze the sensing data and make a decision about channel and the transmission parameters, e.g., transmission power and modulation. Spectrum decision methods proposed for cognitive radio networks consider power consumption as a secondary issue and the amount of extra control packets to transmit is almost never taken into account. Furthermore, nodes in a cognitive radio network have more memory and computational power. More complicated schemes for coordination of spectrum decision, which incur higher communication overhead, may be used in cognitive radio networks [32]. However, these solutions are not feasible for CRSN due to additional challenges posed by the ad hoc multi-hop nature as well as the inherent constraints of sensor nodes.

First, in any given locality, it has been shown that the spectrum sensing results will be similar. Thus, most of the time, spectrum decisions of the nodes, which are close to each other, will be the same. If nodes try to access the channel depending only on their individual spectrum decision results, collision probability increases. Furthermore, since nodes run the same algorithm, when a collision occurs, they all try to switch to another channel, leaving the previous channel empty and colliding again on the new channel. This negates the advantage of multiple channel availability brought by the cognitive radio capability. Therefore, spectrum decision in CRSN must be coordinated to increase overall utilization and maximize power efficiency.

There exist many open research issues for the development of new spectrum decision techniques for CRSN as outlined below.

• Spectrum decision parameters: Determining which parameters to include in the decision process is essential. Parameters such as signal to noise ratio, path loss and channel capacity of the channel are easier to obtain. On the other hand, parameters such as wireless link errors, link layer delays and holding times of PU may be more challenging to obtain by constrained sensor nodes. Therefore, parameters to use in spectrum decision for CRSN must be explored and new algorithms, which yield optimal spectrum decision based on these parameters as well as application-specific requirements, should be developed.

• New decision methods handling heterogeneity: In heterogeneous networks with more than one sensor node type, some of the channel parameters may be more important than others. For example, for a multimedia sensor node which provides streaming video data, channel capacity is more important than path loss. Hence, novel decision schemes which consider heterogeneity in energy-efficient manner must be developed.

• Distribution of control data: Coordinated spectrum decision schemes also need mechanisms to share essential control data. The method vastly used in conventional multi-channel networks is to use a common control channel. However, in general, CRSN do not have channels allocated specifically to them. It was shown in that most of the time, finding a channel that is available through the whole network may be impossible for a secondary user. On the other hand, finding such a channel within a given locality has a large probability and small local group based approaches, in which each group has its own local control channel may be more practical. Therefore, energy efficient central and distributed methods of sharing spectrum decision data must be investigated. Furthermore, analysis and comparison of these central and distributed methods must be studied.

### 2.2.3 Spectrum Handoff

When a PU starts using a previously available channel, CRSN nodes must detect primary user activity within a certain time through spectrum sensing methods as discussed [33]. Then, as illustrated in Fig.2.4, they immediately move to another available channel decided by an effective spectrum decision mechanism as explored in Section 2.2.2, even if they have ongoing transmission. Nodes may also want to switch channels if channel conditions get worse, reducing communication performance. This fundamental functionality of cognitive radio is called as spectrum handoff.

When spectrum handoff is needed, first an alternate channel must be determined. Then, receiver-transmitter handshake must be performed on the new channel. Only then can nodes continue their transmissions. All of these additional operations incur long delays, and hence, buffer overflows which lead to packet losses, degradation in reliability, and ultimately resource waste in CRSN.

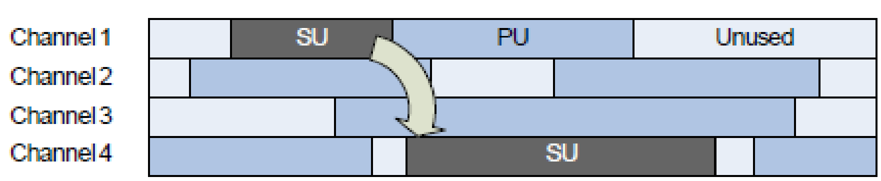


Fig. 2.4 Spectrum handoff in CRSN.

## 2.3 Communications in CRSN

The performance of communication in CRSN is tightly coupled with how effectively dynamic spectrum management issues discussed in Section 3.2 are addressed [34]. There exists a close relation and interaction between the requirements and functionalities of dynamic spectrum management and communication techniques in CRSN as illustrated in Fig.2.5

The design considerations of Physical Layer and data link layer are considered here in detail and explore the existing networking solutions of cognitive radio and wireless sensor networks along with the open research issues for effective communication in CRSN.

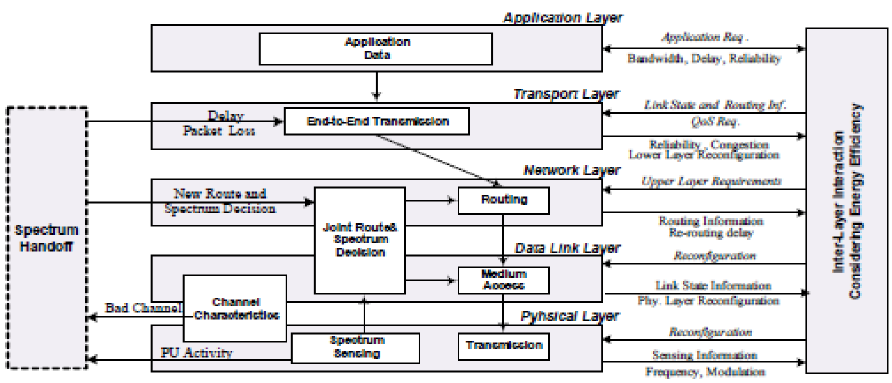


Fig. 2.5 Interaction between the communication and dynamic spectrum management functionalities.

### A. Physical Layer

Physical layer regulates interaction between data link layer and physical wireless medium. It is also responsible for spectrum sensing and reconfiguration of the transmission parameters according to spectrum decisions in CRSN.

A CRSN node can reconfigure its operating frequency modulation, channel coding and output power without hardware replacement [35]. This is the most significant difference between cognitive radio sensor network and wireless sensor network physical layer. Software defined radio (SDR) based RF front-end transmitters and receivers are required for reconfigurability of cognitive radio sensor nodes. However, implementing RF front-end for cognitive radio sensor node is a significant challenge due to low cost and resource-constrained nature of sensor nodes.

On the other hand, limited capabilities of A/D converters used in the nodes and heavy-weight signal processing algorithms, make spectrum sensing a challenging issue as well. Detecting weak signals, and hence, presence of PU, while there are secondary users, are significant sensing problems in CRSN.

Furthermore, unlike in conventional SDR, it is impossible to support different waveforms, since cognitive radio sensor node has limited memory and baseband signal processing capability. Similarly, wide-band spectrum sensing, advanced modulation schemes and cognitive learning capabilities cannot be fully realized in a CRSN node due to its limited computational power.

Clearly, the realization of CRSN depends on the development of effective, energy-efficient, and yet practical cognitive radio for sensor nodes. However, there exist many fundamental open research issues on the physical layer design for CRSN as outlined below:

- Software defined radio-based transceivers providing energy-efficient dynamic spectrum access must be designed for CRSN.
- Low-cost and practical digital signal processing (DSP) hardware and algorithms must be developed for wideband spectrum sensing and reliable detection of primary user overlapping with CRSN.
- Since fully capable SDR is not feasible for CRSN, multiple waveforms cannot be maintained in hardware. Hence, design of an optimal waveform, which can be adaptively used in multiple channels with different transmission parameters, needs to be studied.
- Adaptive methods, which address the trade-off between transmission power and interference, must be designed to solve the interference problem that may arise in densely deployed CRSN.
- Methods to map application-specific QoS requirements to adaptable transmission parameters of the physical layer must be investigated.

### B. Data Link Layer

Data link layer is responsible for reliable transmission and reception of frames between sensor nodes. In general, efficient medium access control (MAC), and error control and correction are the main functionalities of link layer to achieve its goals [36]. In CRSN, these objectives must be achieved in accord with the principles of dynamic spectrum management and in an energy-efficient manner.

1) Error Control: The main error control schemes assumed by WSN are forward error correction (FEC), and automatic repeat request (ARQ). Despite the simplicity of ARQ approaches, its retransmission-based mechanism causes extra energy consumption and reduces bandwidth utilization. Therefore, similar to traditional WSN, FEC schemes are promising for resource-constrained cognitive radio sensor nodes.

2) Medium Access Control: In general, a MAC protocol aims to provide the sensor nodes with means to access the medium in a fair and efficient manner. This is a challenging objective considering the resource limitations of the nodes, dense network deployment, and application-specific QoS requirements.

The main open research issues for data link layer in CRSN are outlined as follows.

- When a degradation in channel conditions is detected, FEC schemes with more redundancy may be used to decrease the error rate. Therefore, dynamic spectrum FEC schemes with minimum energy consumption must be developed. Furthermore, impact of packet size on the transmission efficiency and hence optimal packet size for CRSN must be analyzed under varying channel characteristics.

- Adaptability to the channel conditions enables CRSN to employ novel error prevention schemes. For example, if channel availability permits, transmission bandwidth and constellation size can be changed, keeping the bit rate constant while decreasing error probability. Hence, dynamic spectrum access based novel error control mechanism must be investigated.

- Novel MAC solutions, which can handle the additional challenges above and make full use of the multiple alternative channel availability, must be developed.

- Home channel-based MAC seems to be promising as it requires minimum communication overhead for channel negotiation. However, it is not feasible for CRSN since it requires two transceivers. Methods to adopt home channel idea with a single transceiver in CRSN must be studied.

- Another issue that must be addressed by the link layer is the power saving methods as CRSN nodes have limited power like in WSN. However, due to frequency agility of cognitive radio sensor nodes new challenges arise. One is the coordination of spectrum sensing with sleep/wake up cycles. Another challenge is to provide connectivity to a sensor node after it wakes up. Since there is no fixed channel to transmit, new duty cycle methods jointly considered with neighbor discovery, and spectrum sensing and allocation must be investigated.

## 2.4 Potential Application Areas of CRSN

Traditional sensor networks already have a diverse range of application domains from smart home with embedded sensor and actuators to large-scale real-time multimedia surveillance sensor networks [37]. With the ingression of cognitive radio capability to sensor networks regime, CRSN might be the preferred solution for some specific application domains explored below.

### 2.4.1. Indoor Sensing Applications

Indoor applications, e.g., tele-medicine, home monitoring, emergency networks, factory automation, generally require the deployment of many sensor nodes within a small area. In some cases, such as industrial operation automation, smart building, actor nodes may be also part of the deployment.

The main problem with indoor sensing applications is that the unlicensed bands, e.g., ISM bands, for indoor usage are extremely crowded. Consequently, conventional sensor networks may experience significant challenges in achieving reliable communication due to packet losses, collisions and contention delays. Here, opportunistic spectrum access of CRSN may help mitigate these challenges due to crowded spectrum and extreme node density. For example, with the cognitive radio capability, emergency networks may coexist with other indoor wireless systems. Critical information, which requires real-time reliable communication, may exploit the potential advantages of dynamic spectrum management even in crowded environments.

### 2.4.2. Multimedia Applications

Reliable and timely delivery of event features in the form of multimedia, e.g., audio, still image, video, over resource constrained sensor networks is an extremely challenging objective due to inherent high bandwidth demand of multimedia. At the same time, the capacity provided by the sensor network varies with the temporal and spatial characteristics of the channel.

Unlike the traditional sensor networks, CRSN may provide the sensor nodes with the freedom of dynamically changing communication channels according to the environmental conditions and application-specific quality-of-service (QoS) requirements in terms of bandwidth, bit error rates, and access delay. Hence, for multimedia communication over sensor networks, CRSN may improve the performance of multimedia communication as well as overall spectrum utilization. For example, as the packet travels through multiple hops, each relaying node may use higher frequencies and the highest possible data rate to provide required bandwidth.

Furthermore, when multiple nodes need to transmit at the same time, they try to acquire the same channel which increases the contention delay in WSN. However, nodes in a CRSN have access to multiple available channel and can send their data through different channels concurrently. Therefore, CRSN is more suitable to sensing applications that involve in multimedia communication.

### 2.4.3 Multi-class Heterogeneous Sensing Applications

Some applications may require multiple sensor networks with distinct sensing objectives to coexist over a common area. Various information gathered from these networks may be fused to feed a single decision support. Similarly, in a single sensor network, different sensor nodes may be deployed over the same area to sample the event signal over multiple dimensions including scalar measurements, e.g., heat, humidity, location, motion, as well as audio visual readings of the target being monitored.

Clearly, readings of these heterogeneous sensor networks impose heterogeneity in terms of communication requirements as well. For example, a multimedia sensor node, providing streaming video data, has more bandwidth requirement and less delay tolerance compared to a magnetic sensor. With the help of dynamic spectrum management, multi-class heterogeneous sensor networks may overlap with minimum interference to each other. Furthermore, through the coordination and cooperative spectrum management among these multiple cognitive radio sensor networks, their individual performance as well as the overall spectrum utilization may be improved.

### 2.4.4 Real-time Surveillance Applications

Real-time surveillance applications like target detection and tracking require minimum channel access and communication delay. In traditional WSN with fixed spectrum allocation, this objective may not be always achieved, especially if the operating spectrum band is crowded. Furthermore, additional communication latency may occur in WSN in case of rerouting due to a link failure caused by degrading channel conditions.

In CRSN, sensor nodes may opportunistically access to the available channel in order to maintain minimum access and end-to-end communication delay for effective real-time surveillance applications. As discussed in Section, with the development of new delay-constrained joint spectrum allocation and routing algorithms for CRSN, performance of real-time sensing applications may be further improved. At the same time, statistical information of primary user over the spectrum band in use can be exploited in order to minimize the probability of spectrum handoff so as to avoid increasing communication delay due to frequent spectrum mobility.

One typical real-time sensing application example is military surveillance applications which are highly delay-sensitive and also require high reliability. In general, tactical sensor networks are densely deployed to assure network connectivity and maximize reliability within a certain delay bound. As mentioned above, such dense deployment can also exploit the potential advantages of dynamic spectrum access. Furthermore, with the spectrum handoff capability, tactical surveillance CRSN may be less susceptible to interception and jamming threats.

## 2.5 Summary and Open Research Issues

It can be concluded that most of the spectrum sensing are not suitable for CRSN as they are designed without considering the unique challenges posed by the resource constraints of sensor nodes as follows:

- **Hardware limitations** - It is not feasible to equip CRSN nodes with highly capable processors and A/D units. Thus, complex detection algorithms cannot be used. Spectrum sensing must be performed with limited node hardware.
- **Minimum sensing duration** - Keeping the transceiver on even just for spectrum listening causes excessive power consumption. While sensing accuracy increases with duration, spectrum sensing must be achieved in short sensing duration.
- **Reliable sensing** - Secondary users can operate on licensed bands, unless they do not interfere with primary users. For avoiding interference on primary user, spectrum sensing must be reliable.

The first two of these challenges are unique to CRSN. The last one is a concern for cognitive radio networks too; however, due to limitations of the cognitive radio sensor node, techniques developed for cognitive radio networks cannot be directly applied to CRSN. Therefore, additional research must be conducted on spectrum sensing for CRSN along the following open research issues:

• **Hybrid sensing techniques**: A possible way to obtain spectrum information with minimum sensing duration and low computational complexity is to use hybrid sensing techniques, which is a balanced combination of the sensing approaches above. For example, energy detection may be used on a broader band to have an idea about which portions of the spectrum may be available. Based on this information, more accurate sensing methods can be performed over selected potential channels. Therefore, hybrid sensing techniques addressing the tradeoff between sensing accuracy and complexity must be investigated.

• **Cooperative sensing***:* When nodes rely only on their own spectrum sensing results, they may not be able to detect the primary user due to shadowing. Spectrum sensing duty may be distributed among the nodes to increase sensing accuracy. Achieving sensing in a distributed manner is called cooperative sensing. While cooperative sensing yields better sensing results, it also imposes additional complexity and communication overhead. New cooperative sensing method, requiring minimum amount of extra packet transmission and having minimum impact on the sleep cycles of the node, is an open research issue.

# Spectrum Sensing in CRSN

## 3.1 Spectrum Sensing Techniques for Cognitive Radio

Spectrum sensing is the very task upon which the entire operation of cognitive radio rests. Spectrum sensing, defined as the task of finding spectrum holes by sensing the radio spectrum in the local neighborhood of the cognitive radio receiver in an unsupervised manner [38]. The term spectrum holes stands for those sub bands of the radio spectrum that are underutilized (in part or in full) at a particular instant of time and specific geographic location. To be specific, the task of spectrum sensing involves the following subtasks:

- Detection of spectrum holes;
- Spectral resolution of each spectrum vacancies;
- Identification of the spatial directions of incoming interferes;
- Signal classification.

Sensing of unused spectrum can be based on transmitter detection methods, interference based detection method or cooperative detection methods. Currently investigated transmitter detection methods are matched filter, Eigen-value based detection, cyclo stationary and energy detection. Cooperative detection schemes include centralized, distributed and cluster-based sensing methods. While transmitter and cooperative detection methods sense the spectrum so as not cause interference to the primary transmitter, interference based detection shifts its focus to guarantee minimal primary receiver interference.

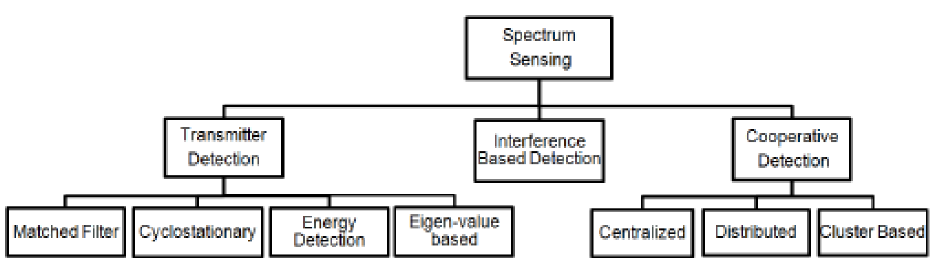


Fig. 3.1 Classification of cognitive radio spectrum sensing

The effectiveness of a detector for certain applications is specified by two parameters; the probability of detection $P_d$ and the probability of false alarm $P_{fa}$ i.e. the performance metrics. High values of $P_d$ ensure less interference to the primary user and low values of $P_{fa}$ ensures high channel throughput. Therefore it is always desirable to have high values for the probability of detection ($P_d$) and low values for the probability of false alarm ($P_{fa}$).

### 3.1.1 Energy Detection

Energy detection is the widely used spectrum sensing method since prior knowledge of the licensed user signal is not required, performs well with unknown dispersive channels and it has less computational and implementation complexity and less delay relative to other methods [39]. However, this method relies on the knowledge of accurate noise power and hence is vulnerable to the noise uncertainty. Energy detection is optimal for detecting independent and identically distributed (iid) signals in high SNR conditions, but not optimal for detecting correlated signals.

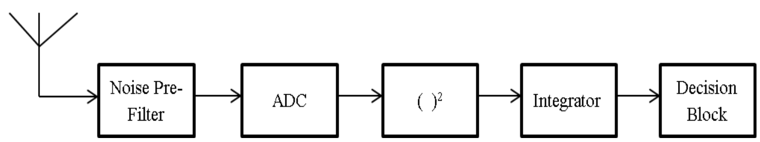


Fig.3.2 Block Diagram of a Simple Energy Detector

Energy detection compares the energy of the received signal in a certain frequency band to a threshold value($\gamma$) which is defined according to the SNR, to derive the two binary hypothesis; whether the signal present or not.

Let the received signal be

$$y(n) = s(n) + w(n) \qquad (1)$$

where s(n) is the signal to be traced, w(n) is the additive white Gaussian noise (AWGN), and n is the sample index. Note that s(n) = 0 when there is no primary user transmission. The decision metric for the energy detector can be formulated as

$$M = \sum_{n=0}^{N} |y(n)|^2 \qquad (2)$$

where N is the size of the observation vector. The the occupancy decision of a band can be obtained by comparing the decision metric M against a fixed threshold $\lambda_E$. It is equivalent to distinguishing between the following two hypotheses:

$$H_0 : y(n) = w(n) \qquad (3)$$

$$H_1 : y(n) = s(n) + w(n) \qquad (4)$$

The performance of the detection algorithm can be summarized with two probabilities: probability of detection $P_d$ and probability of false alarm $P_{fa}$. $P_d$ is the probability of detecting a signal on the considered frequency when it is really present. Hence a large detection probability is desired. It can be written as

$$P_d = P(M > \lambda_E \mid H_1) \qquad (5)$$

$P_{fa}$ is the probability that the test incorrectly decides that the considered frequency is occupied when it actually is not, and it can be formulated as

$$P_{fa} = P\left(M > \lambda_E \mid H_0\right) \qquad (6)$$

$P_{fa}$ should be kept as small as possible in order to prevent underutilization of transmission opportunities. The decision threshold $\lambda_E$ can be fixed for finding an optimum balance between $P_d$ and $P_{fa}$. However, this requires knowledge of noise and detected signal powers. The noise power can be calculated, but the signal power is tough to estimate as it changes depending on ongoing transmission characteristics and the distance between the cognitive radio and primary user. In practice, the threshold is selected to obtain a certain false alarm rate. Hence, knowledge of noise variance is sufficient for selection of a threshold.

The threshold value (λ) for the detector is determined either from the fixed probability of detection Pd or from the fixed probability of false alarm Pfa. The evaluation procedure of the detection threshold (λ) from the Probability of false alarm Pfa is called the Constant False Alarm Rate (CFAR) principle. An approach which involves the calculation of the detection threshold (λ) from the already fixed target Pd is called the Constant Detection Rate (CDR) Principle. The conventional practice is to follow CFAR principle since it does not demand channel SNR information to be known.

The detection probability $P_d$ and false alarm probability $P_{fa}$ in a non-fading channel can be derived using the cumulative distribution functions of the central and non-central chi square distributions.

$$P_{fa} = P\{M > \lambda \mid H_0\} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \qquad (7)$$

$$P_d = P\{M > \lambda \mid H_1\} = Q_m\left(\sqrt{2u\gamma}, \sqrt{\lambda}\right) \qquad (8)$$

### 3.1.2 Matched Filter Detection

Matched filter detection can achieve a shorter sensing time for a certain probability of false alarm or probability of detection but it requires the accurate synchronization and the priory knowledge of primary user's features such as bandwidth, modulating type and order, operating frequency and pulse shaping, which would be possible only if the licensed user intends leveraging cooperation [40]. For demodulation it has to achieve coherency with primary user signal by performing timing, carrier synchronization and channel equalization and power is consumed to demodulate the signal. Detecting above features and implementing matched filter detection is possible when primary users are recognizable in pilots, preambles, synchronization words or spreading codes that can be used for coherent detection.

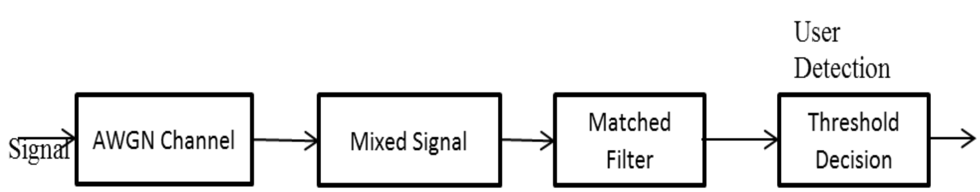


Fig.3.3 Matched Filter Detection

### 3.1.3 Feature Detection

Transmitted signals have cyclo stationary features which are caused by periodicity or statistics of mean or autocorrelation of the signal and cyclo-stationary detector exploits these features to detect the presence of the primary user. Modulated signals in general are associated with periodicities such as digital sequences in the form of pulse trains, sine wave carriers, repeating spreading or having cyclic prefixes which result in an inherent autocorrelation in these communication signals. A cyclo stationary detector detects the presence of a signal based on the periodicity of the transmission by using a spectral correlation function (SCF) instead the power spectrum density (PSD) [41]. Noise, in general, is wide sense stationary and indicates no periodicity; hence the cyclo stationary detector can differentiate the permanent user signal easily from the noise pattern.

Unlike the matched detector, cyclo-stationary feature detector does not require transmitter information at the CR. Under uncertain noise powers and low SNR it can perform better than the energy detector. Nevertheless cyclo-stationary detector requires excessive signal processing capabilities and is computationally very complex to implement.

### 3.1.4 Eigen Value Based Detection

Eigen value based detection is a novel method which is based on the Eigen values of the covariance matrix of the received signal at the secondary users. The expression for decision threshold has been derived based on the random matrix theory (RMT) which is also under research and in a developing stage.

This method achieves both high $P_d$ and low $P_{fa}$ without requiring information of the primary user signals, channel and noise power as a priori hence it can overcome the noise uncertainty problem faced by energy detectors [42]. Further, no synchronization is needed as in matched filter detection. Since the covariance matrix incorporates the correlations among the signal samples, the Eigen value based detection outperform the energy detection in the presence of correlated signals while its performance is comparable to that of the energy detector in the presence of independent and identically distributed (iid) signals. But it is computationally more complex than the energy detector.

There are three main Eigen value based detection methods under study, which are classified according to the test statistic used to detect the signal. The test statistic is compared against a computed threshold. The three methods are the maximum minimum Eigen value (MME), energy with minimum Eigen value (EME) and maximum Eigen value detection (MED). MME method uses the ratio of the maximum Eigen value to minimum Eigen value of the sample covariance matrix as the test statistic. While EME method employs the ratio of the average power of the received signal to minimum Eigen value. In MED method the maximum Eigen value is used as the test statistic to be compared against a threshold.

### 3.2 Co-operative Spectrum Sensing for CRSN

The transmitter detectors operate as individual nodes. Depending on the spatial distribution, secondary nodes have access to different primary users and hence face problems imposed by hidden node, shadowing, multipath and receiver uncertainty (inability of a CR to detect a primary transmitter due to weakness of its signal but CR's transmission is adversely affecting the reception of the primary receiver). Information collected at each individual CR can be combined in decision making to address the above mentioned issues and cooperative detection employs this technique.

Advantages of cooperative detection methods are their ability to prevent hidden node, shadowing, multipath and receiver uncertainty problems and high accuracy. These are achievable at the cost of traffic overhead caused by the implementation complexity, the need for a control channel and the delay incorporated with the communication between CRs and data processing. In a cooperation based spectrum sensing scheme, the measurements of several secondary users are combined and examined together in order to determine the presence of the primary user.

When fusing the data cooperative schemes can either use hard decisions or soft decisions to evaluate whether the primary signal is present. In hard decision making, individual CRs make the decisions regarding the existence of the primary user and the final decision is made by fusing these decisions from individual cognitive users together. The hard decision can be made using either the OR rule or the AND rule. Under the OR rule, if one of the sensing cognitive users decides that the primary user is present then all the cooperating CRs accept that the primary signal is present whereas under the AND rule, only if all the cognitive users decide that the primary user is present, entire system will accept that the primary is present [43]. An optimum value for $P_d$ or $P_{fa}$ can be obtained by considering only the decisions of CRs with higher SNR, for the decision making. Other suboptimal hard decision schemes in use are the Counting Rule and Linear quadratic detector. In counting rule a threshold value is determined and if the number of users that decide that the primary user is present is above a threshold value, then this decision is accepted by the entire system, else it is rejected. Linear quadratic detector uses partial statistical knowledge, without ignoring the correlation information completely, to give a general suboptimal solution to the fusion problem and gives a better performance than the one obtained by ignoring the correlation information entirely.

In soft decision making, the decision is made by correlating the measurements collected by the individual users rather than the decisions of the individual users. It has been shown that soft decision making has much better results when compared to hard decision making. A weighted linear combination of the measurements of cognitive users is taken for decision making. The weights are chosen so as to maximize the value of $P_d$ for a given value of $P_{fa}$. Larger weighting coefficients are assigned to secondary users which receive high SNR signals and are likely to make their local decisions consistent with the real hypothesis, allowing more contribution to the global decision making. Lesser weights would be assigned to secondary users experiencing deep fading, limiting their contribution to the global decision making.

### 3.2.1 Centralized Co-operative Spectrum Sensing

Centralized cooperative spectrum sensing uses regulator dependent management where a central unit collects sensing information from CR devices and identifies the available spectrum and allocate the unused spectrum to the secondary users that require access to the spectrum by the use of methods such as spectrum pooling and spectrum leasing. But if the number of devices is large, the data traffic between nodes would be highly crowded and a larger bandwidth would be required.

### 3.2.2 Distributed Co-operative Spectrum Sensing

Distributed co-operative Detection does not require a backbone infrastructure and final information is learnt from the closest node, hence it has less traffic over head compared to centralized cooperative detection. Still it has disadvantages such as network information overhead and band width consumption. In distributed cooperative detection, cognitive nodes share information among neighbors but they make their own decisions as to which part of the spectrum they can use.

### 3.2.3 Cluster-based Co-operative Spectrum Sensing

In cluster based spectrum sensing, the most favorable user with the largest reporting channel gain in a cluster is selected as the cluster head. The cluster heads collect the sensing results from all the other users in the same cluster and forward them to the common receiver, which coordinates the CRs. After receiving the authorization from the common receiver, through cluster heads, all the cognitive users initiate the spectrum sensing independently [44]. The cluster heads collect local observations in the same cluster and make a cluster decision according to a fusion function. If the control channel bandwidth is low, radios exchange decisions or summary statistics rather than long vectors of raw data. On the other and if the control channel bandwidth is high, CRs can exchange entire raw data. Next the cluster decisions are reported to the common receiver, which would make a final decision according to a fusion function. After determining the occupancy of the spectrum the common receiver transmits back the final decision to the CRs via cluster heads and informs which secondary users are allowed to transmit.

## 3.3 Adaptive Threshold Based Energy Detectors

Energy detection, inherently the most appropriate spectrum sensing technique for CRSNs fails to deliver at low SNR conditions. An adaptive threshold based energy detector is considered to improve the performance metrics of the detector in CRSN at low SNR conditions. The target metric Pd or Pfa is identified from the nature of the application and efforts have been concentrated on maintaining a constant value for the metric irrespective of the channel dynamics i.e. varying SNR [45]. Here the threshold ($\lambda$) is adaptive in the sense it is not permanently based on target Pfa or Pd i.e. the available channel is being monitored and the estimated channel information is used for switching the threshold. An adaptive control parameter $\alpha$ is introduced to vary the threshold adaptively to maintain the performance characteristics within the required range.

Fig.3.4 shows the block diagram of an adaptive threshold based energy detector. The channel estimator collects the channel information and this information together with other parameters allows the threshold decision module to choose the right threshold value so as to optimize the performance metric. Using (9) and (11) and substituting the mean and variance values from (4) to (7), the expression for critical number of samples turned out to be

$$Nc = (1/\gamma^2)*[Q^{-1}(Pfa)-Q^{-1}(Pd)*(\sqrt{2\gamma+1})]^2 \qquad (9)$$

The significance of (9) is that it gives the critical number of samples, $N_c$, required to achieve the target metrics ($P_d$ & Pfa) i.e. $N_c$ allows to decide on how best to switch the threshold from one value to another to achieve the target $P_d$& $P_{fa}$.

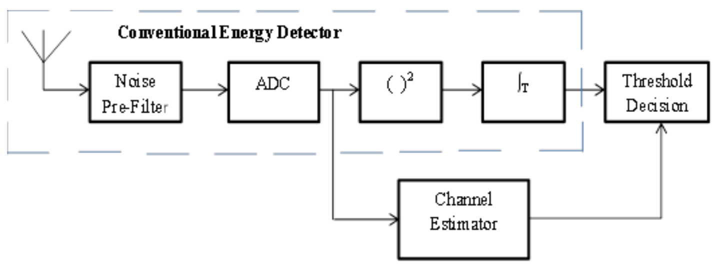


Fig.3.4 Block Diagram of Adaptive Threshold Energy Detector

### 3.3.1 To Improve the Throughput

Initially, the threshold value is calculated from a target $P_{fa}$ and the system is expected to do a channel estimation process immediately to get SNR ($\gamma$) value. Then it is in a position to calculate the critical number of samples required to reach the target performance metric. If the system can sense the channel long enough to get the required number of samples Ns so that $N \geq N_c$ then the threshold ($\lambda$) can be switched to $\lambda_d$ by changing $\alpha$ value to zero. If the situation does not allow the system to sense for long time then threshold ($\lambda_f$) should be maintained to keep low $P_{fa}$ values. A control parameter $\alpha$ is introduced to vary the threshold from $\lambda_d$ to $\lambda_f$ or vice versa. The threshold $\lambda$ is written as

$$\lambda = \lambda_d + \alpha\,(\lambda_f - \lambda_d),\ 0 \leq \alpha \leq 1 \qquad (10)$$

The parameter $\alpha$ can take values from [0,1] thereby changing the threshold from $\lambda_d$ to $\lambda_f$.

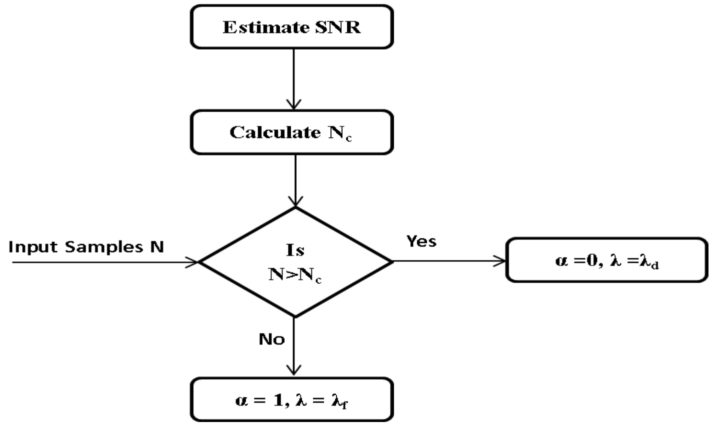


Fig.3.5 Flow chart describing the Procedure to Achieve High Throughput

### 3.3.2 To Reduce the Interference

The channel estimator estimates the channel initially and provides the SNR information to the decision system. Now the system can calculate the critical number of samples required to reach the target performance metric i.e. $P_d$. If the system can sense the channel long enough to get the required number of samples Ns so that $N \geq N_c$ then the threshold ($\lambda$) can be switched to $\lambda_f$ by changing $\alpha$ value to zero. If the situation does not allow the system to sense for long time then threshold ($\lambda$) should be maintained in $\lambda_d$ to be remained in higher $P_d$ range. A control parameter $\alpha$ is introduced to vary the threshold from $\lambda_d$ to $\lambda_f$ or vice versa. The threshold $\lambda$ is written as

$$\lambda = \lambda_f + \alpha\,(\lambda_d - \lambda_f),\ 0 \leq \alpha \leq 1 \qquad (11)$$

The parameter $\alpha$ can take values from [0,1] thereby changing the threshold from $\lambda_f$ to $\lambda_d$.

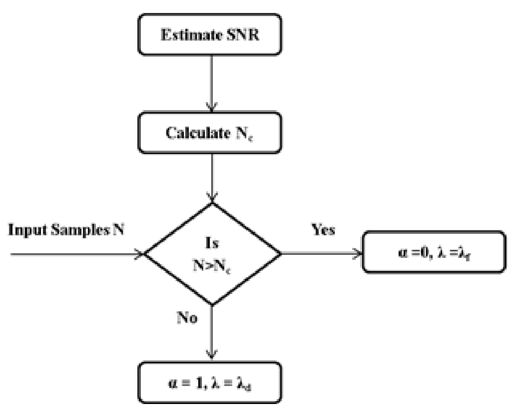


Fig.3.6 Flow chart describing the Procedure to Reduce the Interference

## 3.4 Results & Discussion

### A. Energy Detection

3.4.1 Receiver Operating Characteristics (ROC) for Simple Energy Detection at -12 dB

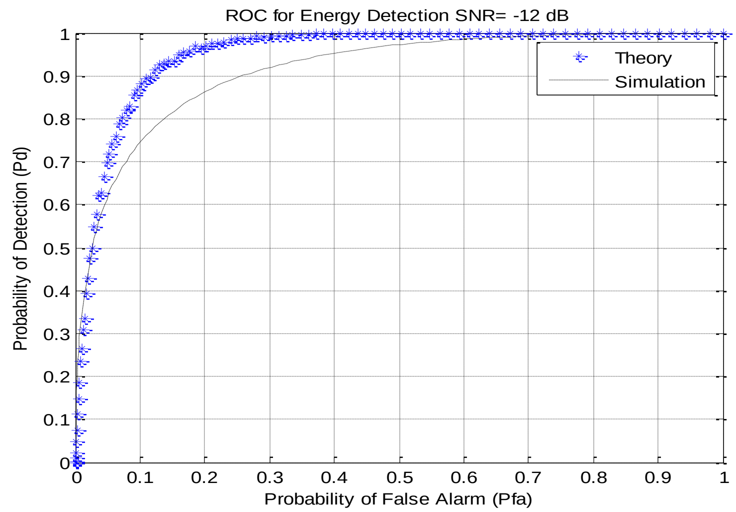


Fig. 3.4.1 ROC for Energy Detection at -12 dB

3.4.2 Probability of Detection V/S Number of Samples under Different SNR Values

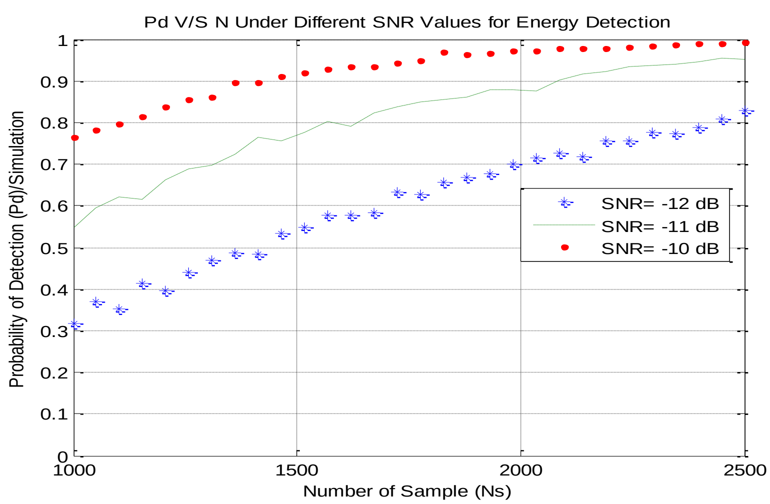


Fig.3.4.2 $P_d$ V/S $N_s$

### 3.4.3 Receiver Operating Characteristics (ROC) for Energy Detection under different SNR

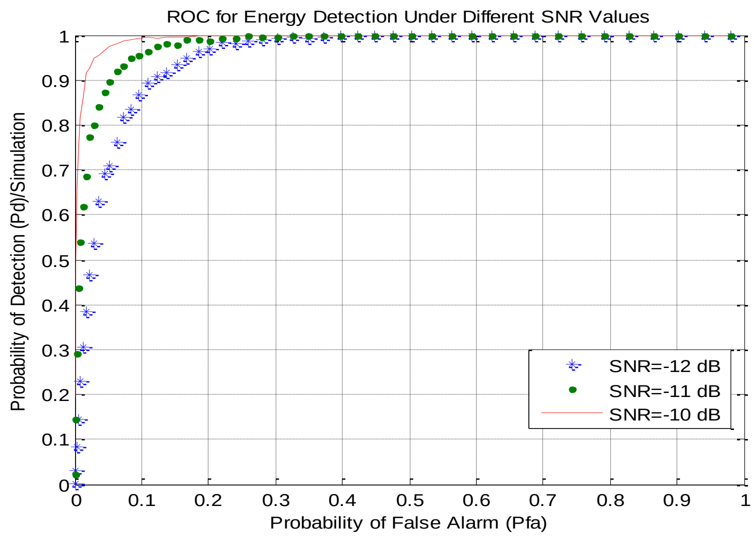


Fig.3.4.3 ROC for Energy Detection under different SNR

### 3.4.4 Receiver Operating Characteristics for Co-operative Detection using different Rules

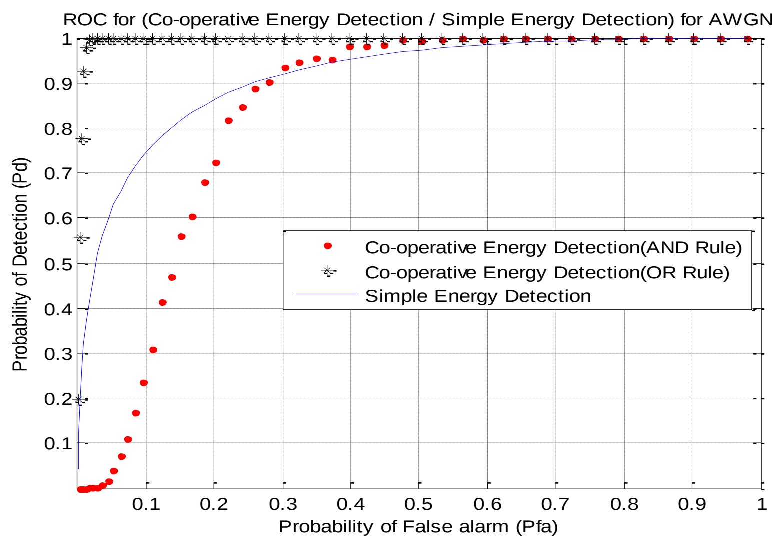


Fig.3.4.4 ROC for Co-operative Detection

3.4.5 OFDM transmitted signal in Time Domain

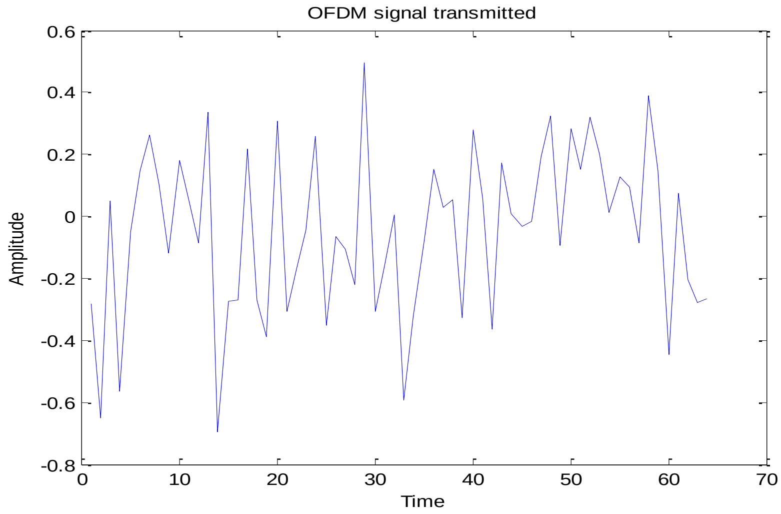


Fig. 3.4.5 OFDM transmitted signal in Time Domain

3.4.6 OFDM Spectrum Transmitted

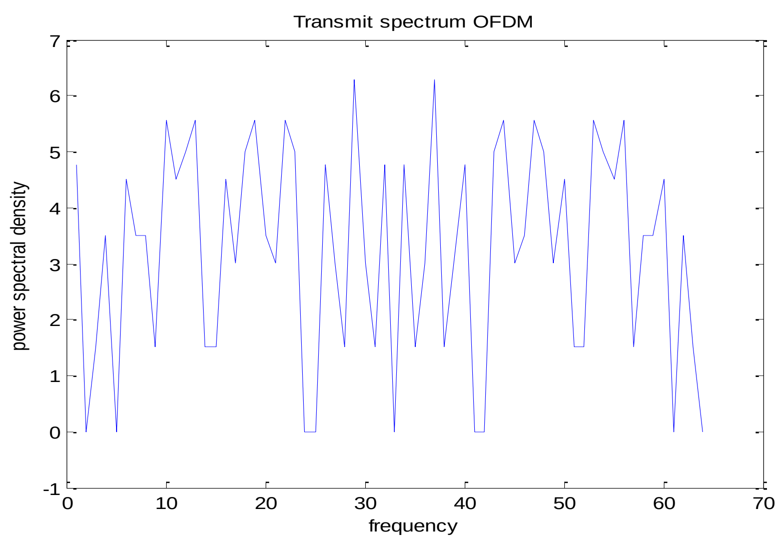


Fig.3.4.6 OFDM Spectrum

3.4.7 Receiver Operating Characteristics of Energy Detection for OFDM transmission

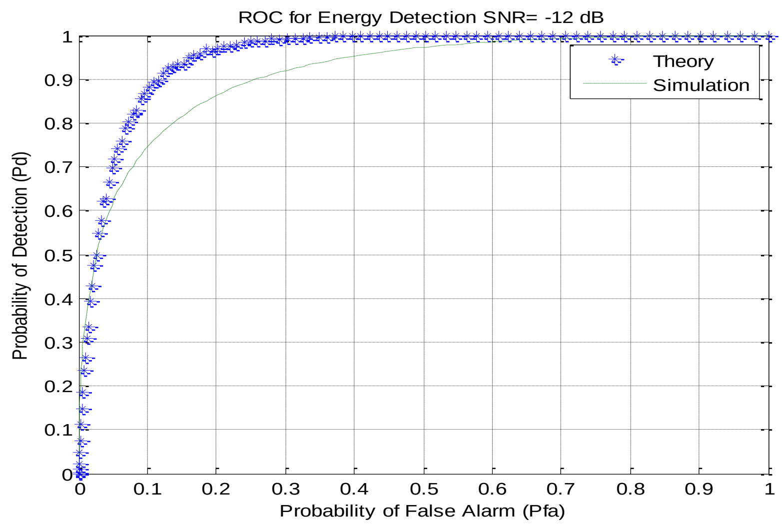


Fig.3.4.7 ROC of ED for OFDM transmission

## B. Matched Filter

3.4.8 Input Data to be transmitted

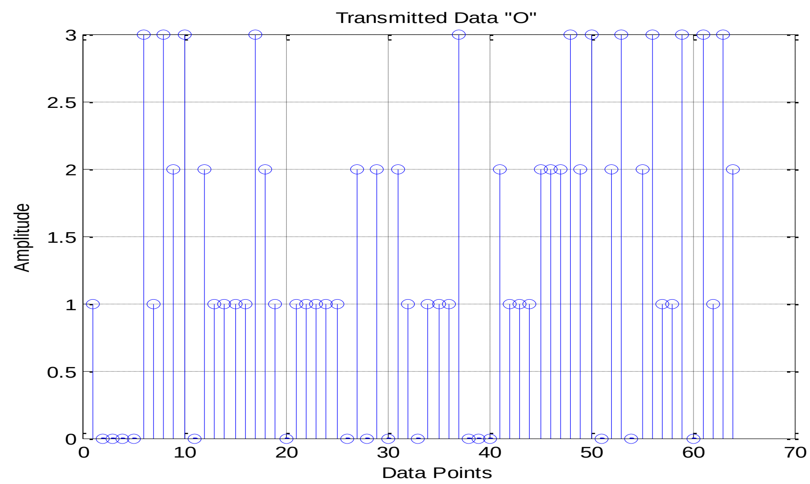


Fig.3.4.8 Message Signal

3.4.9 Constellation Diagram for the modulated signal

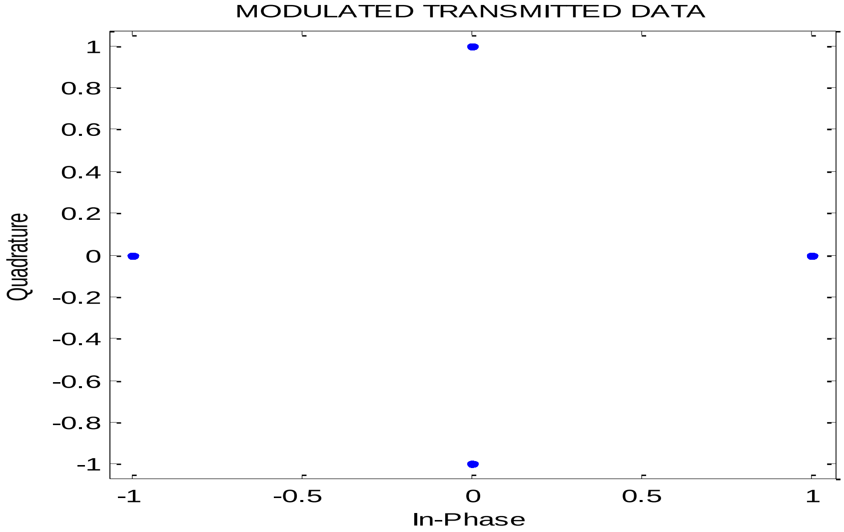


Fig 3.4.9 Constellation Diagram

3.4.10 Time Domain Representation of Transmitted OFDM Signal

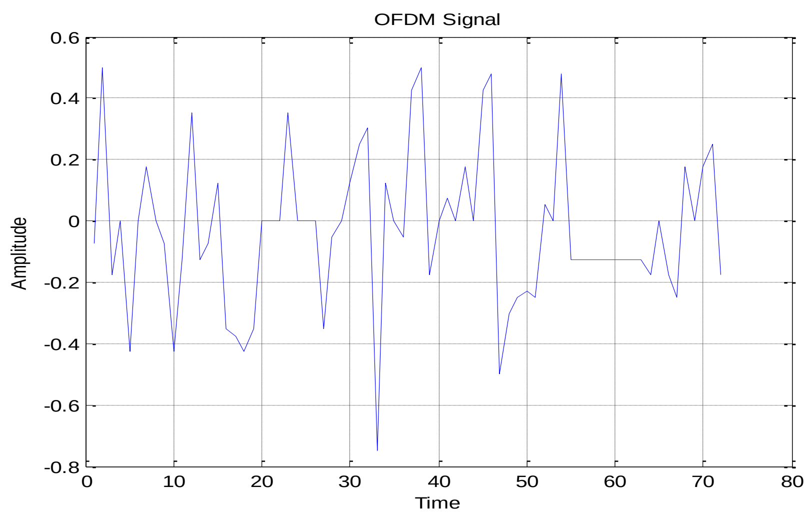


Fig.3.4.10 Transmitted OFDM Signal in Time Domain

3.4.11 OFDM Signal after HPA

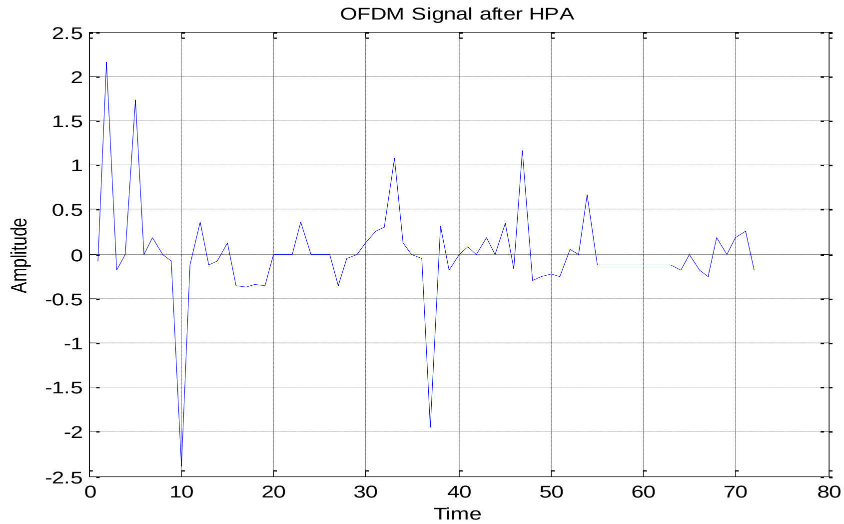


Fig.3.4.11 OFDM Signal after HPA

3.4.12 Autocorrelation Function for Matched Filter

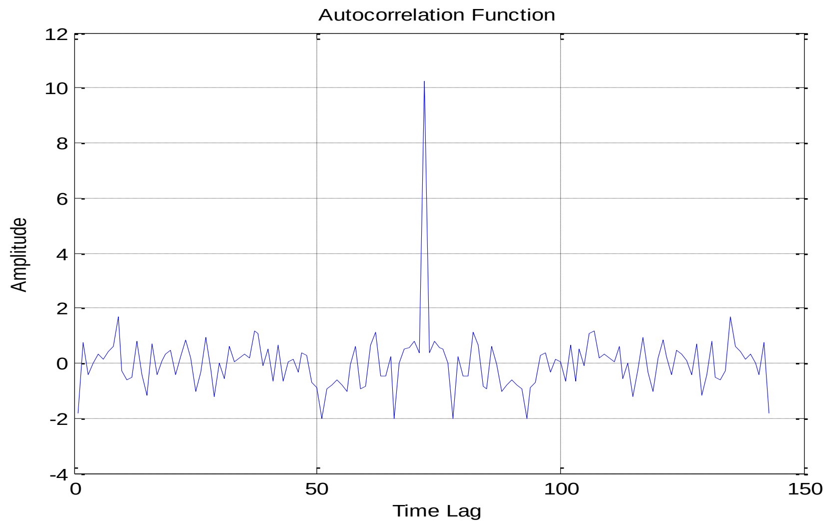


Fig.3.4.12 Autocorrelation Function

3.4.13 Receiver Operating Characteristics for Matched Filter

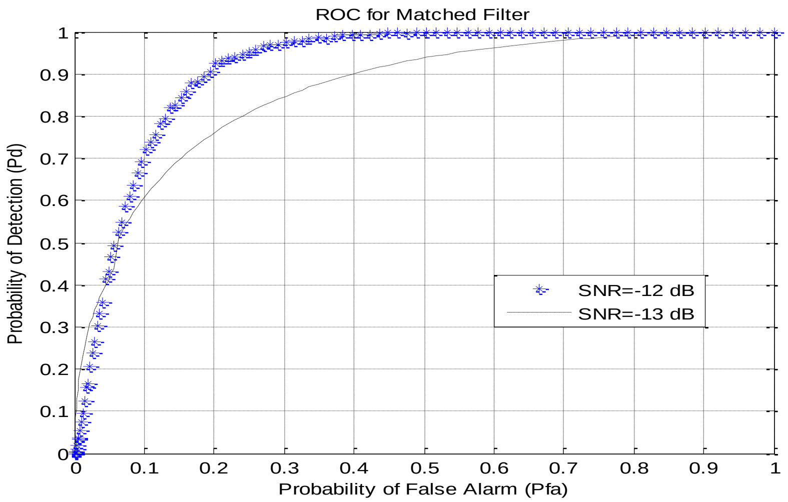


Fig 3.4.13 ROC for Matched Filter

## C. Cyclo-stationary Detectors

3.4.14 Receiver Operating Characteristics for Cyclo-Stationary Detection under different SNR

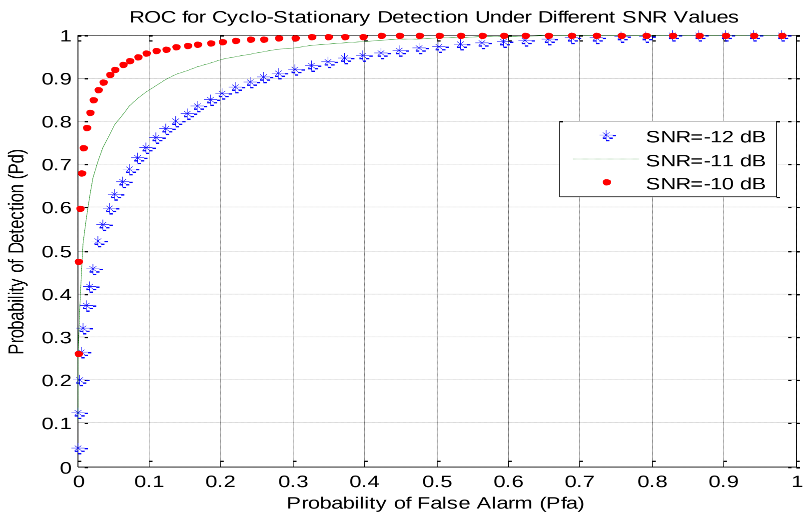


Fig. 3. 4.14 ROC for Cyclo-Stationary Detection

## D. Eigen Value Based Detectors

3.4.15 Receiver Operating Characteristics for Eigen Value Based Detectors

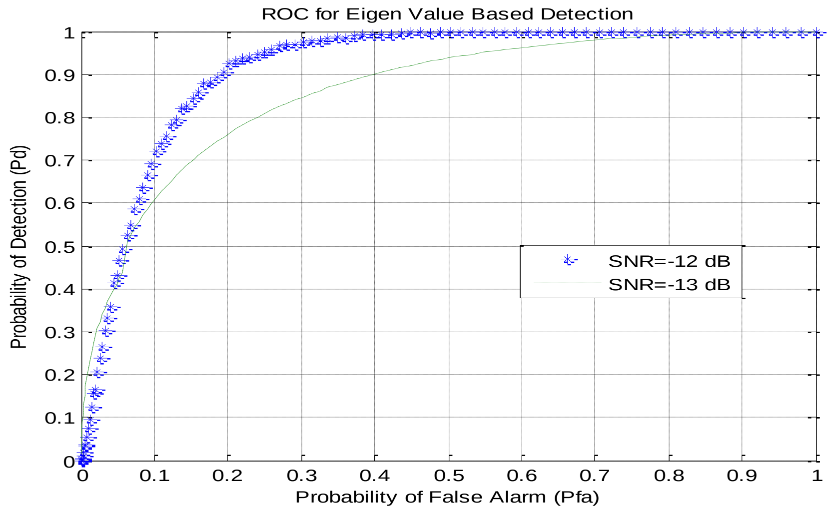


Fig 3.4.15 ROC for Eigen Value Based Detection

## E. Adaptive Threshold Based Energy Detection

3.4.16 Probability of Detection $P_d$ for Energy Detection by $P_{fa}$ Based Threshold

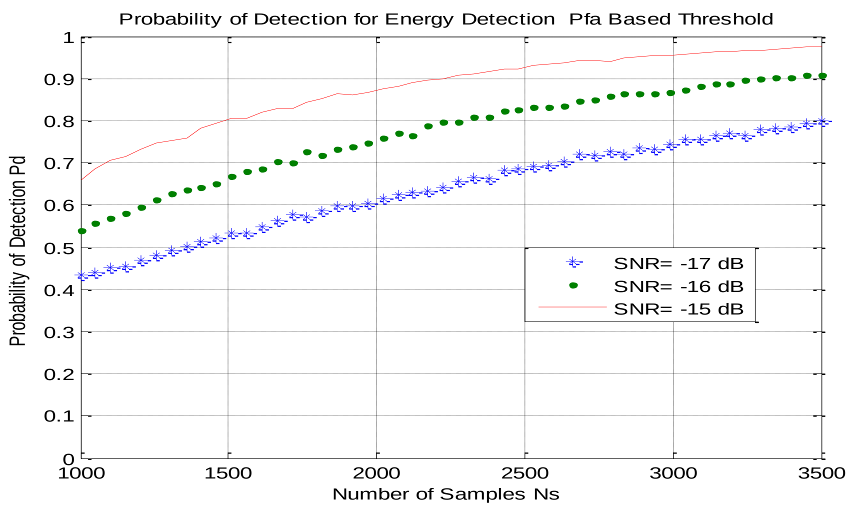


Fig.3 4.16 $P_d$ for ED by $P_{fa}$ Based Threshold

3.4.17 Probability of Detection $P_d$ for Energy Detection by $P_d$ Based Threshold

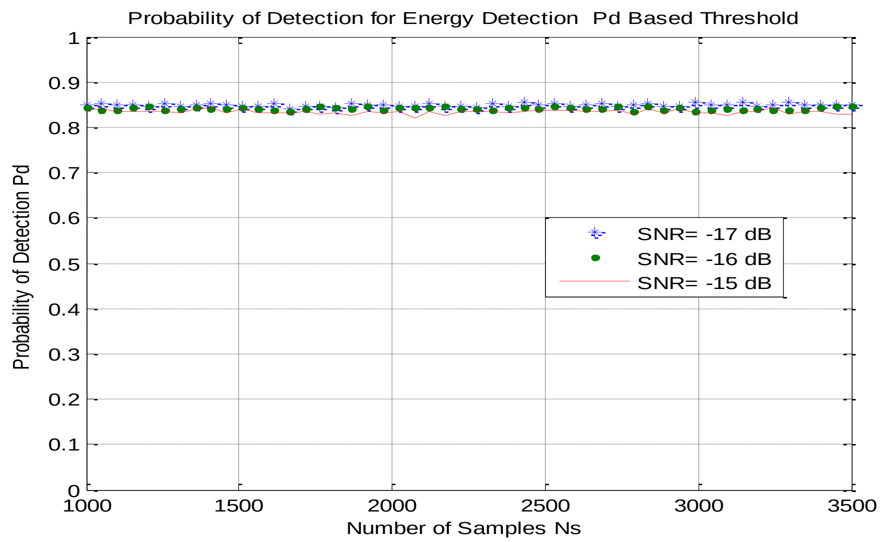


Fig.3 4.17 $P_d$ for ED by $P_d$ Based Threshold

3.4.18 Probability of False Alarm $P_{fa}$ for Energy Detection by $P_d$ Based Threshold

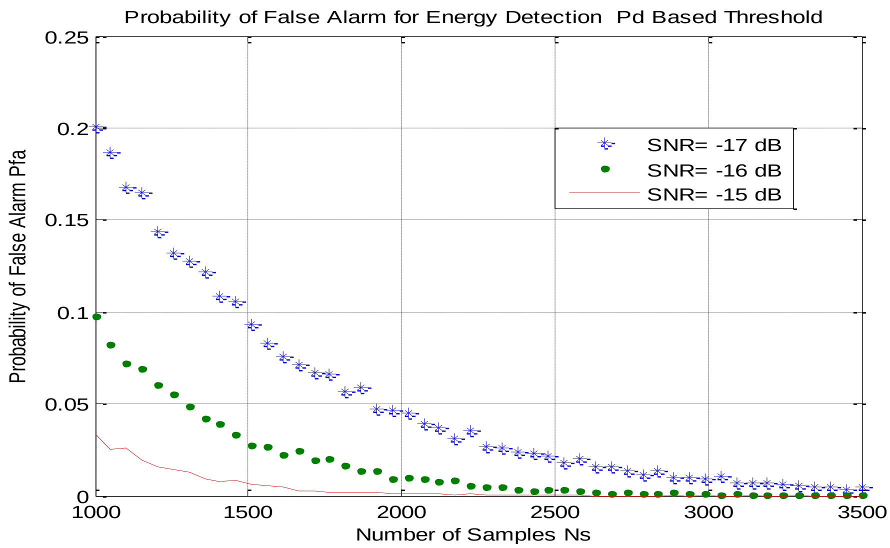


Fig.3 4.18 $P_{fa}$ for ED by $P_d$ Based Threshold

### 3.4.19 Probability of False Alarm $P_{fa}$ for Energy Detection by $P_{fa}$ Based Threshold

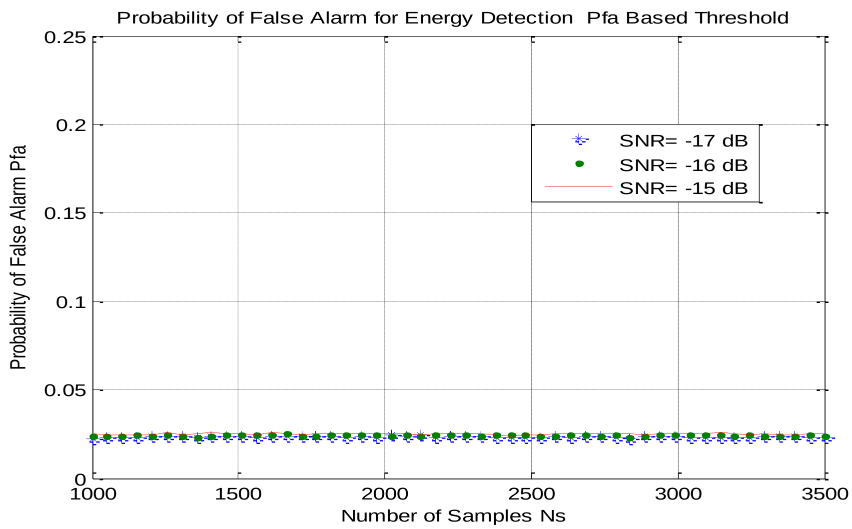


Fig.3 4.19 $P_{fa}$ for ED by $P_{fa}$ Based Threshold

### 3.4.20 Probability of False Alarm V/S Number of Samples for different alpha values

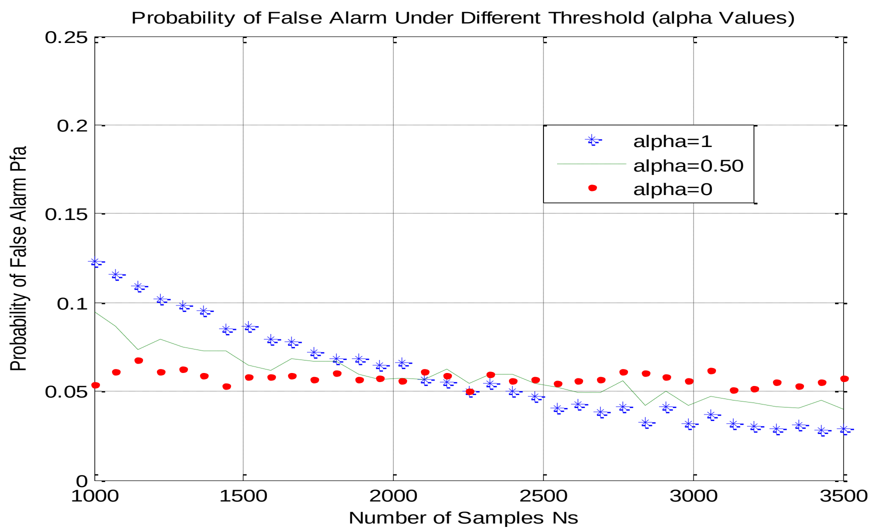


Fig.3.4.20 $P_{fa}$ V/S $N_s$ for Different alpha Values

3.4.21 Probability of Detection V/S Number of Samples for different alpha values

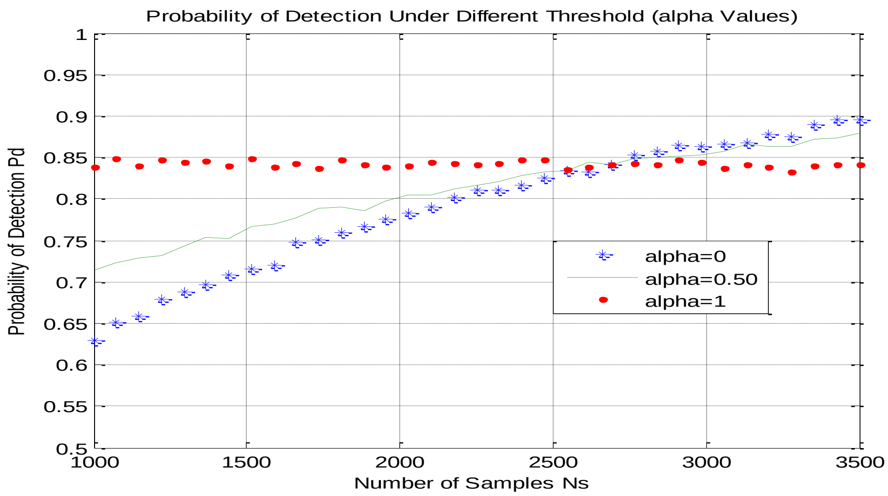


Fig.3.4.21 $P_d$ V/S $N_s$ for Different alpha Values

## 3.5 Summary

Co-operative spectrum sensing which shares sensing information between the nodes is found to be the most appropriate sensing strategy for CRSN. Simple energy detection inherently the most preferred spectrum sensing scheme for CRSN under moderate SNR values fails to deliver at low SNR conditions due to multipath fading and shadowing. Adaptive threshold based energy detectors can be used to either improve the throughput or reduce the interference in a Cognitive Radio Sensor Network (CRSN) scenario.

# Hybrid Co-operative Spectrum Sensing Schemes

## 4.1 Hybrid Spectrum Sensing

A possible way to obtain spectrum information with minimum sensing duration and low computational complexity is to use hybrid sensing techniques, which is a balanced combination of the sensing approaches above. For example, energy detection may be used on a broader band to have an idea about which portions of the spectrum may be available [46]. Based on this information, more accurate sensing methods can be performed over selected potential channels. Therefore, hybrid sensing techniques addressing the tradeoff between sensing accuracy and complexity must be investigated.

## 4.2 Energy Detection-Cyclo stationary Detection

To increase accuracy and optimize the detection probability of cognitive radio user a hybrid sensing algorithms is proposed. Actually this algorithm is the cascading result of the Energy based sensing and Cyclo stationary feature detection. From literature we know that energy based detection is simpler as compared to Cyclo stationary feature detection [47]. On the basis of this logic the output of the primary transmitter is allowed to pass first from Energy based detector and then from Cyclo stationary feature detector. In this Hybrid sensing algorithm the energy based detector is used to verify whether primary user is present or not. Here Cyclo stationary algorithm is used just to get the features (modulation, operating frequency, no. of signal) of primary user when primary is present and is used as detector when energy detector is not sure about the presence or absence of primary user. So this algorithm basically divides the tasks between Energy based detector and Cyclo stationary feature detection. Actually the energy based detection is used as detector and Cyclo stationary feature detection is used as feature extractor when primary user is present. This feature of algorithm provides flexibility to switch to the tasks on need basis. The block diagram of this hybrid algorithm is shown below in figure 4.1.

Flow chart is also given in figure 4.2 from flow chart the output of the primary signal is first given to energy based detector. At this stage when the output of the detector is 1, it indicate the presence of primary user, then the features of signal is calculated by Cyclo stationary feature extractor, when output is 0 this indicates that primary user is absent, also if the output is neither 0 nor 1 (N mean not sure) then energy detector pass this report to the Cyclo stationary feature detector. The Cyclo stationary feature detector reviews it and adjudicates primary user is present or not. When the output of Cyclo stationary feature detector is 0 it indicates the absence of primary user but when its output is either 1 or >0 then it is considered as primary user is present.

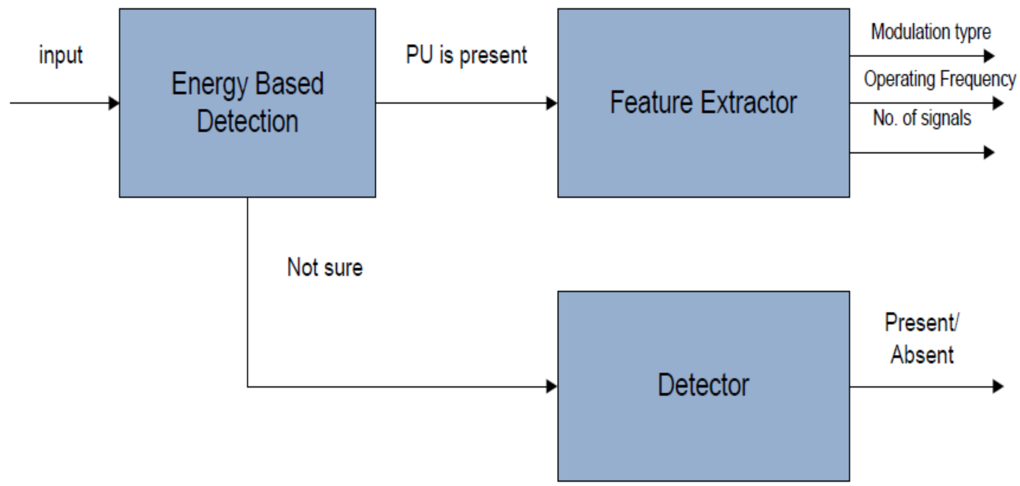


Fig.4.1: Block diagram of Cyclo-stationary Hybrid sensing algorithm

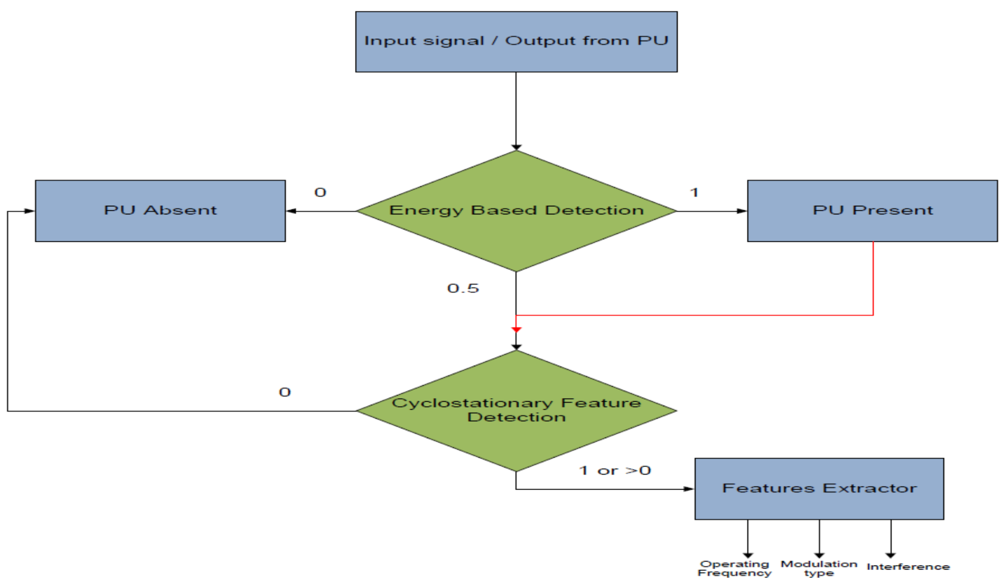


Fig .4.2: Flow chart of Hybrid sensing algorithm

## 4.3 Energy Detection-Eigen Value Based Detection

A new hybrid spectrum sensing scheme which involves simple energy detector and Eigen value based detector is proposed to enhance the performance of CRSN without any previous knowledge about the primary users and their properties [48]. All cognitive radio sensor nodes are equipped with a modified simple energy detection scheme with two appropriate energy threshold values $\xi 1$ and $\xi 2$ where $\xi 1$ is the lower threshold value and $\xi 2$ is the upper threshold value respectively. When a cognitive radio sensor node detects a signal to be in the range between $\xi 1$ and $\xi 2$, cluster head transfer this information to the detection center. Detection centers employing Eigen value based detector which does not demand any prior information about the signal or its characteristics is responsible for making a final decision on signal detection.

Eigen value based spectrum sensing relies on algorithms developed on the Eigen values of the sample co-variance matrix, determined from the received signal at the cognitive sensing node. Eigen value based spectrum sensing can be mainly employed using two algorithms, based on the ratio of maximum to minimum Eigen value (MME) and based on the ratio of average signal power to the minimum Eigen value (EME). Maximum to minimum Eigen value (MME) algorithm is analyzed and applied here for the second phase of sensing in detection center and using random matrix theory (RMT) concepts, we evaluated and analyzed the detection and false alarm probabilities also.

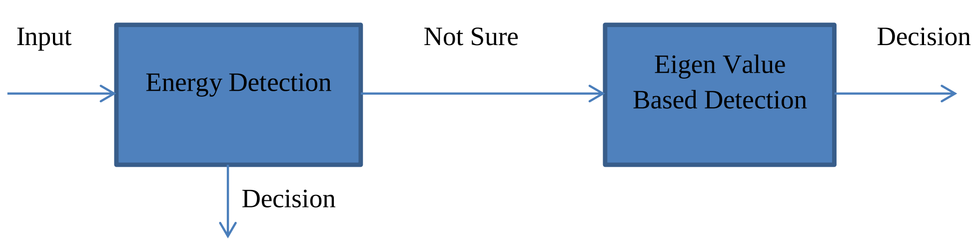


Fig .4.3: Block diagram of Eigen Value Based Hybrid sensing algorithm

## 4.4 Results and Discussion

## Hybrid Spectrum Sensing

4.4.1 Receiver Operating Characteristics for Two Different Hybrid Spectrum Sensing Schemes

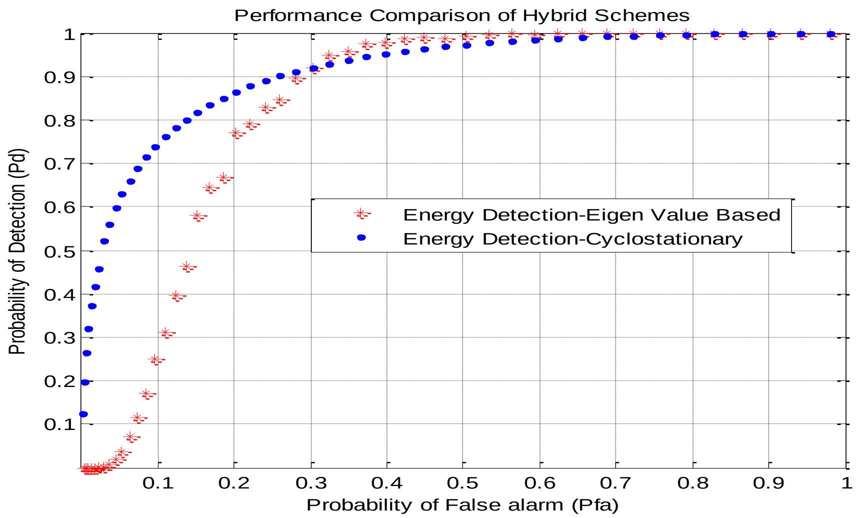


Fig.4.4.1 ROC Comparison for two different Hybrid Spectrum Sensing Schemes

4.4.2 Probability of False Alarm $P_{fa}$ for Two Different Hybrid Spectrum Sensing Schemes

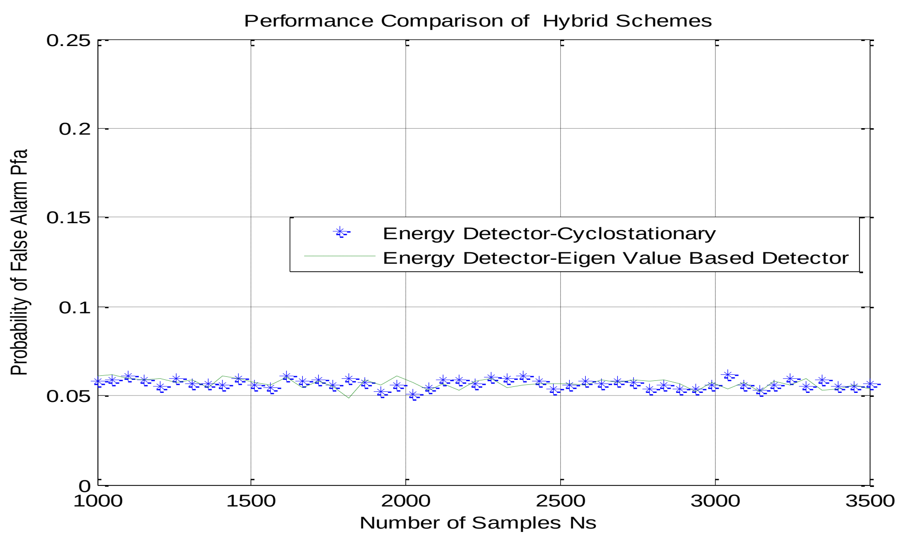


Fig.4.4.2 $P_{fa}$ for two different Hybrid Spectrum Sensing Schemes

### 4.5 Summary

Hybrid spectrum sensing schemes which in co-operates two or more spectrum sensing schemes performs well in fading and shadowing CRSN environment. The proposed hybrid scheme comprised of Energy Detector and Eigen Value Based Detector is proved to be a suitable sensing mechanism for resource constrained CRSN. The performance of two hybrid sensing schemes comprised of energy detector -cyclo-stationary detector and energy detector-eigen value based detector are simulated and compared under moderate SNR values.

# Conclusion

## 5.1 Introduction

The research work carried out for this thesis, investigates the best spectrum sensing technique available for the resource constrained nature of Cognitive Radio Sensor Networks (CRSN). Spectrum sensing in resource constrained, shadowing and fading environment of CRSN with receiver uncertainties is a more challenging task than conventional spectrum sensing in cognitive radio networks. Co-operative spectrum sensing techniques can improve the cognitive radio network performance by enhancing spectrum efficiency and spectrum reliability by effectively combating the destructive effects present in the CRSN environment at the cost of comprises in overhead traffic, power consumption, and complexity and control channels. The identification of an appropriate spectrum sensing scheme for CRSN is a challenge within the constraints of wireless sensor nodes. Efforts have been concentrated to develop energy efficient and a cost effective co-operative spectrum sensing techniques which performs well in fading and shadowing environment.

Following this introduction, section 6.2 lists the achievements of the research work. Section 6.3 provides the limitations in the study and section 6.4 presents some of the future research area that can be extended to this thesis.

## 5.2 Contribution of the thesis

The first two chapters of the thesis give an introduction to Wireless Sensor Networks (WSN) and its applications, Cognitive Radio, the features of Dynamic Spectrum Access, Cognitive Radio Sensor Networks (CRSN) and background literature survey. The third chapter presents a detailed discussion about CRSN, Dynamic Spectrum Management Aspects in CRSN, Communications in CRSN and potential application areas of CRSN. The main theme of this thesis is focused on various spectrum sensing techniques applied for Cognitive Radio Sensor Networks is discussed in chapter 4. Transmitter based detection techniques like Energy Detection, Matched Filter, Cyclo-Stationary Detector and Eigen Value based Detectors are covered in depth. Co-operative Spectrum Sensing and its favorability to CRSN is discussed then followed with the discussion of adaptive threshold based energy detectors to improve the throughput and to reduce the interference. Simulation results are presented to analyze the performance of various spectrum sensing schemes. Chapter 5 focus on Hybrid Spectrum Sensing Schemes which are a combination of two or more Detection Schemes and analyze its performance in a CRSN environment.

The contribution of the thesis can be viewed as an attempt to identify the appropriate spectrum sensing strategy for Cognitive Radio Sensor Networks within its constraints. Energy detection, inherently the most appropriate spectrum sensing technique for CRSNs fails to deliver at low SNR conditions**.** Adaptive threshold based energy detectors are introduced to improve the performance of simple energy detectors at low SNR conditions and can be extended to improve the throughput and to reduce the interference as well. A hybrid spectrum sensing scheme comprised of energy detector and eigen value based detector is proposed to enhance the performance of CRSN under its unique constraints.

## 5.3 Limitations

This section presents some of the limitations of the work reported in this thesis. Not all the resource constraints of sensor nodes are considered here for the analysis. The fading and shadowing channel is modeled using Signal to Noise Ratio (SNR) term only and no other fading parameters or multi path components are considered here for the analysis.

## 5.4 Future Directions

There exist many fundamental open research issues on the physical layer design for CRSN as outlined below:

- Software defined radio-based transceivers providing energy-efficient dynamic spectrum access must be designed for CRSN.
- Low-cost and practical digital signal processing (DSP) hardware and algorithms must be developed for wideband spectrum sensing and reliable detection of primary user overlapping with CRSN.
- Since fully capable SDR is not feasible for CRSN, multiple waveforms cannot be maintained in hardware. Hence, design of an optimal waveform, which can be adaptively used in multiple channels with different transmission parameters, needs to be studied.

- Adaptive methods, which address the trade-off between transmission power and interference, must be designed to solve the interference problem that may arise in densely deployed CRSN.
- Methods to map application-specific QoS requirements to adaptable transmission parameters of the physical layer must be investigated.

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# Publications

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[2]. Hareesh K and Poonam Singh, “An Adaptive Threshold Based Energy Detection Algorithm to Improve the Throughput in Cognitive Radio Sensor Networks (CRSNs)” IEEE Conference on Information and Communication Technologies (ICT 2013) (Accepted).

[3]. Hareesh K and Poonam Singh, “An Adaptive Threshold Based Energy Detector for CRSN to Reduce Interference’’ in IEEE International Conference on Communication and Signal Processing-ICCSP'13 Melmaruvathur, Tamilnadu, India (Accepted).